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IEEE Std 3006.8™-2018

Recommended Practice for Analyzing Reliability Data for Equipment Used in Industrial and Commercial Power Systems

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IEEE Recommended Practice for Analyzing Reliability Data for Equipment Used in Industrial and Commercial Power Systems

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Abstract: Data supporting the reliability evaluation of existing industrial and commercial power systems are described. This recommended practice is likely to be of greatest value to the power-oriented engineer with limited experience in the area of reliability. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

Keywords: availability, IEEE 3006.8™, mean down time (MDT), mean time between failures (MTBF), mean time to maintain (MTTM), mean time to repair (MTTR), reliability analysis, reliability data

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At the time this IEEE recommended practice was completed, the Power Systems Reliability Working Group had the following membership:

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When the IEEE-SA Standards Board approved this recommended practice on 27 September 2018, it had the following membership:

Introduction

This introduction is not part of IEEE Std 3006.8-2018, IEEE Recommended Practice for Analyzing Reliability Data for Equipment Used in Industrial and Commercial Power Systems.

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When this project is completed, the technical material included in the 13 IEEE Color Books will be included in a series of new standards—the most significant of which will be a new standard, IEEE Std 3000™, IEEE Recommended Practice for the Engineering of Industrial and Commercial Power Systems. The new standard will cover the fundamentals of planning, design, analysis, construction, installation, startup, operation, and maintenance of electrical systems in industrial and commercial facilities. Approximately 60 additional dot standards, organized into the following categories, will provide in-depth treatment of many of the topics introduced by IEEE Std 3000™:

- Power Systems Design (3001 series)
- Power Systems Analysis (3002 series)
- Power Systems Grounding (3003 series)
- Protection and Coordination (3004 series)
- Emergency, Standby Power, and Energy Management Systems (3005 series)
- Power Systems Reliability (3006 series)
- Power Systems Maintenance, Operations, and Safety (3007 series)

In many cases, the material in a dot standard comes from a particular chapter of a particular IEEE Color Book. In other cases, material from several IEEE Color Books has been combined into a new dot standard.

IEEE Std 3006.8™

Knowledge of the reliability of electrical equipment is an important consideration in the design and operation of industrial and commercial power distribution systems. Each of the hundreds of components installed at a facility has an operational signature defined by its failure statistics. When these signatures are analyzed in the context of their relationship in a power system, designers and operators can understand—and more importantly, predict—system performance over time. In response, this recommended practice offers the best facility equipment data currently available. The data that follow represent five decades, millions of dollars, and thousands of hours of labor in the collection of data from more than 300 diverse facilities.

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IEEE Recommended Practice for Analyzing Reliability Data for Equipment Used in Industrial and Commercial Power Systems

1. Overview

1.1 Scope

This recommended practice describes how to analyze reliability data for equipment used in industrial and commercial power systems. Equipment reliability data collected over the years is presented. This is followed by a discussion of key equipment reliability metrics, such as failure rate, downtime to repair in hours per failure, and probability of starting (operating).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

Historical Reliability Data for IEEE 3006 Standards: Power System Reliability™.[1,2]

IEEE Std 3006.2-2016™, Recommended Practice for Evaluating the Reliability of Existing Industrial and Commercial Power Systems.

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[3]

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For definitions of terms pertaining to power system reliability used in this standard, refer to IEEE Std 3006.5™-2014.

4. Introduction

Knowledge of the reliability of electrical equipment is an important consideration in the design and operation of industrial and commercial power distribution systems. Each of the hundreds of components installed at a facility has an operational signature defined by its failure statistics. When these signatures are analyzed in the context of their relationship in a power system, designers and operators can understand—and more importantly, predict—system performance over time. In response, this recommended practice offers the best facility equipment data currently available. The data that follow represent five decades, millions of dollars, and thousands of hours of labor in the collection of data from more than 300 diverse facilities.

The failure characteristics of individual pieces of electrical equipment can be partially described by the following basic statistics: mean time to repair (MTTR) and mean time between failures (MTBF). From these, most failure statistics can be calculated, including and especially, reliability (r) and inherent availability (a_i). Data on other factors (e.g., cause and type of failures, maintenance procedures, repair method, etc.) are also required to characterize the performance of electrical equipment in service (refer to *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 1 and page 61 for more information).

Availability is a key measure of facility performance. Many facilities operate for long periods of time, providing power to perform critical functions. Balancing the cost of design, construction, and maintenance against the requirement for continuous and reliable operation is of the utmost importance. Understanding both component-level and system-level failure statistics is essential to achieving this balance.

The data in this recommended practice are used to model power system performance. The analytical models required for estimating power system performance are presented in IEEE Std 3006.3™-2017 [B21], IEEE Std 3006.5™-2014, and IEEE Std 3006.9™-2013 [B23].

The recommended practice is divided into three parts, which together cover data collection programs spanning more than 45 years. Each part consists of a large collection of equipment reliability and availability statistics.

Part 1 includes data from two major collection efforts conducted by the U.S. Army Corps of Engineers Power Reliability Enhancement Program (USACE-PREP). The 1994 data collection program was extensive, including information for many types of commercial facilities within the United States. The 2005 program replicated and expanded upon the 1994 program, respecting its standards for data integrity. Together, these efforts created the most comprehensive facility equipment reliability database in existence.

Part 2 is a collection of equipment surveys conducted between 1976 and 1994. The resolution is remarkable, as it specifically divulges cause of failure, a valuable piece of knowledge for facility managers.

Part 3 is a collection of equipment surveys conducted before 1976. The data in this collection reveal detail about failure modes, time of failure discovery, and how failures were repaired following discovery. The data also give failure data for utility providers in a variety of configurations and voltage classes.

Each of the three parts complements the others, providing focused data to key indicators of equipment performance. Details of the survey data (Part 2 and Part 3) are unavailable to statistically merge with the data collected in Part 1; the raw individual component information from the data collection has been lost over time.

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[3] *IEEE Standards Dictionary Online* is available at: http://dictionary.ieee.org.

An additional archive of data can be found in *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*. This document contains information according to Table 1.

Table 1—Historical reliability data for IEEE 3006 Standards reference guide

Electrical equipment types	*Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*
Motors, > 50 hp (37.3 kW)	pages 1, 61, 124
Motor starters	pages 1, 61
Generators	pages 1, 61, 187
Circuit breakers	pages 1, 61, 161, 170, 266
Disconnect switches	pages 1, 61
Bus duct	pages 1, 61
Switchgear bus, insulated	pages 1, 61, 100
Open wire	pages 1, 61
Cable	pages 1, 61, 151
Transmission lines, 230 kV and above	page 221
Electric utility power supplies	pages 1, 61, 95

The IEEE Industry Applications Society (IAS) has also conducted surveys on the reliability of electrical equipment in industrial and commercial installations (see Aquilino [B4], Dickinson [B6], IEEE Committee Reports [B11], [B12], [B13], [B29], and O'Donnell [B28], [B30]).

5. Part 1: Mechanical and electrical equipment data, 1994 and 2005

5.1 Database development

5.1.1 Summary of contents

The data presented in this section is the culmination of more than 50 000 h of effort to collect operational and maintenance data on 280 power generation, power distribution, and HVAC equipment items, including generators, switchgear assemblies, cables, boilers, piping, valves, and chillers.

A database was developed to assist technical staff in organizing, tracking, analyzing, and reporting all of the technical and contact information during the execution of these projects. The database contains:

a) Contact and site records. These records ensure data is unique by keeping accurate accounts of what information has been accepted and what has been rejected from different sites. These records also allow data analysts the opportunity to follow-up with facility managers to complete or update data records. Nearly 400 sites have been contacted or surveyed to provide data; approximately 300 have provided data that meets the standards for inclusion in the database.

b) Equipment records. These include all of the specific reliability and maintainability information for each component. The database contains information for 280 component types. This includes some 370 000 individual pieces of equipment, 900 000 failure and maintenance event records, and 1 900 000 unit-years of equipment operation. In many cases, records also contain more detailed information, such as failure mode, cause of failure, manufacturers, operating modes, etc.

A comprehensive database system allowed the program to record site information, prioritize site visits, collect and organize data, input and verify data, summarize and analyze data, and produce reports. The output record generator contains several canned reports designed for data summary and availability

calculations. Some of the reports are designed to allow the user the flexibility to select a multitude of query topics.

The database software and structure has evolved as the database has grown. The current version is contained in a common software package with a user-friendly front-end graphical user interface. Recent design changes allowed new data to be automatically uploaded, reducing manual labor and increasing accuracy.

5.1.2 Data collection

Contacts were the key to the success of this program. The cooperation and support of the people involved from the many facilities is demonstrated in the quality of data received to support the data collection.

A concerted effort was employed to develop an extensive contact database using manufacturers, facilities, societies, and locations of any potential data contributor utilizing key electrical, mechanical, and control components. The collection teams sought manufacturers for contacts as well as warranty information, 25 of which participated. A total of 25 professional societies were also contacted, including:

a) American Gas Association

b) National Association of Power Engineers

c) American Society of Mechanical Engineers

d) Association of Physical Plant Administrators

e) Association of Energy Engineers

The final list of sites includes universities, government facilities, prisons, utilities, office buildings, and other types of facilities. Specifics of these contributors are withheld to protect the confidentiality of the sources.

Building and managing the database requires a broad focus, looking into how each additional site contributes to the database as a whole. In order to collect statistically valid data it was important that a stratified survey of different facility categories, applications, and operating conditions be conducted. Guidelines were developed to assist in the selection of potential sites that vary in (a) degree of maintenance, (b) facility type, (c) component size, and (d) equipment age.

Collecting diversified data was critical to covering the spectrum of how equipment may operate and fail. To locate sites with equipment and data collection policies that conform to the standards of the database, surveys were first issued to hundreds of candidate facilities. Those that responded with potential for inclusion were visited by the data collection team. The team then copied the data, to be later pushed through the rigorous quality assurance process. The procedure for conducting the survey is given in *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 109. Information on the determination and analysis of reliability studies is presented in IEEE Std 500™-1984 [B18].

5.1.3 Data summarization and classification

As with every data collection program, there are varying degrees of completeness in the data gathered. Some data sources had complete records and could give statistics on operational characteristics on every piece of equipment from the installation date through the collection date. More often, the only items tracked were major items, such as cooling towers and generators. Other problems included incomplete or non-current versions of the equipment drawings.

It became important to categorize the different levels of data completeness to ensure that the final data collection included fair data representation for each component. In other words, it is important to avoid a bias stemming from record quality. To quantify this data completion (or quality) index, the collection team identified these four levels:

a) *Perfect data:* Data needed for a valid, complete reliability study, including a parts list, failure history data with time-to-failure statistics, parts description data, operational periods, and five continuous years of recorded data. No engineering judgment or data extrapolation is required. The USACE-PREP equipment record database is composed of 10% to 20% of this type of data.

b) *Imperfect data:* Data without serious flaws, but the data collection process demanded additional time to ensure useful information was gathered. Examples include parts list determined by inspection, incomplete drawings, or less than five years of data. The USACE-PREP equipment record database contains 35% to 40% of this type of data.

c) *Verbal/inspection data:* Data with serious gaps that required additional documentation and verification prior to its inclusion in the database. Items included were typically major items, such as generator sets and boilers. Senior maintenance personnel were interviewed to extract the necessary information to fill the data gaps. These interviews were used as support documentation of recorded data, not as data source information. About 25% of this type of data exists in the USACE-PREP equipment record database.

d) *Soft data:* Data that relied on the memories of experienced maintenance personnel from the participating facility; it was often extracted from log books containing maintenance personnel entries, filing cabinets with work order forms, and repair records when outside repair support was needed. Engineering judgment was often used to determine numerous performance parameters. This type of data was the most difficult and time consuming to summarize, and was only used when other data sources were unavailable and when it could be sufficiently completed to meet the input standards. The USACE-PREP equipment record database is composed of 10% to 15% of this type of data.

These levels helped determine the effort required to identify and categorize the components at the site. Engineers prepared all candidate data for analysis through a process called *summarization*. The database requires all information to be imported in correct and consistent format. Engineers assemble all known data for a subject component in tables, including nameplate information, such as make, model, serial number, install/removal date, etc., and failure and maintenance event information, such as date of incident, outage duration, cause of event, type of event, etc. Engineers purged data for other types of equipment outside of the database scope.

5.1.4 Maintenance policy

One objective of the data collection effort was to minimize the effects of maintenance policies and procedures on the calculated availability values by collecting data from a variety of locations having various maintenance policies. The database team developed a code to categorize each facility's maintenance policies and procedures into one of three levels:

a) Code 1: Above average maintenance policy. The facility not only followed a scheduled, preventive maintenance policy that was equivalent or similar to the manufacturer's suggested policy, but also went beyond it, such as using redundant units, specialized equipment tests (thermograph, vibration analysis, oil analysis), complete spare parts kits for equipment, and so on. The USACE-PREP equipment database is composed of 25% of this type of data.

b) Code 2: Average maintenance policy. The facility used either in-house maintenance crews performing scheduled, preventative maintenance according to the equipment manufacturer's

suggested preventive maintenance schedule, or a combination of in-house maintenance crews and outside contractors. In both cases, it was verified that they did actually follow a fairly rigid schedule. The USACE-PREP equipment database is composed of 58% of this type of data.

c) Code 3: Below average maintenance policy. The facility's actual policy was slightly lower than average. It may have instituted a scheduled maintenance policy but not followed it, or it may have had no maintenance policy. Symptoms such as leaky valves with rags tied around them, dirty air filters, squeaky bearings, loose belts, and lax general housekeeping because of unavailable labor were typical signs that maintenance policies were less than desirable. The USACE-PREP equipment database is composed of 17% of this type of data.

Each location was then compared to each other and to the average maintenance policy. Overall, the facilities that the collection teams visited practiced an average level of maintenance; that is, they adhered to the manufacturer's recommended maintenance policies. The team looked at approximately the same number of facilities that had below average maintenance policies as those facilities that had an above average maintenance policy.

5.1.5 Analysis and inclusion

Engineers used test statistics (goodness-of-fit, Weibull) to compare candidate data to established populations of reliability data. Significant outliers warranted a review of the data set being considered. If the new data set was both an outlier and showed suspicious site data (e.g., data gaps, mistakes) the data set was rejected. A statistical outlier alone was not a sufficient reason to reject candidate data.

Following the analysis, engineers made accept/reject decisions for every candidate data set. A computer algorithm processed all accepted data, verifying formatting, data types, and other information. Engineers reviewed an output file for each submission, confirming that data was incorporated into the database as expected.

5.2 Results

5.2.1 USACE-PREP equipment reliability database

The final USACE-PREP database includes the 280 different components. A hierarchical structure provides the analyst with options to use a specific type of component or data for a general category of components. As an example, the *category* of Accumulator comprises two *classes* (pressurized and unpressurized). Reliability data are presented for each class and for the entire category of Accumulators.

Some categories of equipment are more complete than others. Though not a perfect proxy, unit-years can be used to interpret the confidence in a data point. A few components have less than 10 unit-years of information available; many have more than 10 000. When using information from the database, the analyst may opt to use a data point for a category of equipment, which may be a more reliable statistic than a data point for a specific class.

Table 2 displays the average failure and maintenance statistics of the data collection described in Part 1.

Table 2—USACE-PREP equipment reliability database

Category			Class	Unit-years	Failures	Failure rate (failures/year)	MTBF (hours)	MTTR (hours)	MTTM (hours)	MDT (hours)
Accumulator				**1463.2**	**10**	**0.006 834 233**	**1 281 782**	**7.80**	**0.94**	**0.98**
	Pressurized	H01-100	Accumulator, pressurized	1072.8	7	0.006 525 131	1 342 502	10.29	0.96	1.01
	Unpressurized	H01-200	Accumulator, unpressurized	390.4	3	0.007 683 510	1 140 104	2.00	0.33	0.42
Air compressor				5124.5	1592	0.310 662 877	28 198	12.20	1.55	4.24
	Electric	H02-100	Air compressor, electric	4534.6	1492	0.329 029 093	26 624	11.80	1.48	4.16
	Fuel	H02-200	Air compressor, fuel	590.0	100	0.169 499 396	51 682	17.45	2.72	5.71
Air conditioner	All types	H03-000	Air conditioner	4947.4	781	0.157 860 257	55 492	5.95	1.59	2.63
Air dryer	All types	H04-000	Air dryer, all types	2307.2	170	0.073 681 948	118 889	9.11	1.44	5.36
Air handling unit				12 173.7	2650	0.217 681 964	40 242	5.06	1.99	3.27
	Humid			379.1	68	0.179 375 438	48 836	2.55	2.53	3.21
		H05-110[a]	Air handling unit, humid, pan humid, w/o drive	25.0	0	0.027 695 536	429 882	0.00	0.00	0.00
		H05-130	Air handling unit, humid, pan humid, with drive	212.8	30	0.140 975 629	62 138	3.02	2.73	2.94
		H05-120[a]	Air handling unit, humid, spray humid, w/o drive	38.1	0	0.018205276	653 976	0.00	0.00	0.00
		H05-140	Air handling unit, humid, spray humid, with drive	103.2	38	0.368 256 160	23 788	2.27	1.59	4.31
	Multizone system	H05-310	Air handling unit, multizone system, packaged	1103.7	448	0.405 891 785	21 582	6.18	4.34	9.97
	Non-humid			10 690.9	2134	0.199 609 243	43 886	4.75	1.67	2.38
		H05-210	Air handling unit, non-humid, without drive	7821.1	1734	0.221 709 225	39 511	4.95	1.88	2.40
		H05-220	Air handling unit, non-humid, with drive	2869.8	400	0.139 380 939	62 849	4.18	1.51	2.36
Air separator	All types	H06-000	Air separator, all types	84.7	9	0.106 272 848	82 429	6.31	0.88	3.35
Surge arrester	Surge and lightning	E01-000	Surge arrester, surge and lightning	1863.4	12	0.006 439 803	1 360 290	9.50	12.28	11.66
Battery	Rechargeable			13 228.7	121	0.009 146 782	957 714	13.40	0.16	0.45
		E02-110	Battery, gel cell-sealed	3106.8	53	0.017 059 514	513 496	2.00	0.13	0.15
		E02-120	Battery, lead acid	5022.6	65	0.012 941 467	676 894	24.08	0.25	4.31
		E02-130	Battery, nickel-cadmium	5099.3	3	0.000 588 315	14 889 985	10.33	0.16	0.16

Blower				4307.0	239	0.055 490 708	157 864	9.44	0.17	0.63
	Without drive	H07-100	Blower, without drive	3947.4	189	0.047 880 115	182 957	10.75	0.17	0.32
	With drive	H07-200	Blower with drive	359.7	50	0.139 016 903	63 014	3.79	1.04	24.95
Boiler				5125.6	2190	0.427 265 681	20 502	17.69	6.61	8.72
	Hot water	H08-100	Boiler, hot water	2566.6	688	0.268 055 191	32 680	3.94	6.35	6.89
	Steam			2559.0	1502	0.586 952 425	14 925	24.40	6.70	9.37
		H08-210	Boiler, steam, high pressure, > 103.4 kPa (15 psig)	942.7	781	0.828 434 093	10 574	39.77	5.52	6.84
		H08-220	Boiler, steam, low pressure, ≤ 103.4 kPa (15 psig)	1616.2	721	0.446 097 568	19 637	13.25	48.03	40.86
Bus duct or busway	All types	E03-000	Bus duct or busway, all types, per 30.5 m (100 ft)	2462.3	143	0.058 075 621	150 838	1.65	1.08	1.26
Cabinet heaters	Forced air flow			14 053.8	64	0.004 553 920	1 923 618	3.10	1.23	1.56
		E04-100	Cabinet heaters, forced air flow, steam or hot water	13 931.1	64	0.004 594 025	1 906 825	3.10	1.23	1.56
		E04-200[a]	Cabinet heaters, forced air flow, electric	122.7	0	0.005 649 689	2 107 341	0.00	0.67	0.67
Cable				736 799.6	1366	0.001 853 964	4 725 011	5.59	4.34	4.43
	AC			698 824.2	924	0.001 322 221	6 625 216	7.29	4.35	4.50
		E06-111	Cable, ac, 0 V to 600 V, above ground, in conduit, per 305 m (1000 ft)	29 442.9	2	0.000 067 928	28 959 932	8.00	13.06	13.01
		E06-112[a]	Cable, ac, 0 V to 600 V, above ground, in trays, per 305 m (1000 ft)	15.9	0	0.043 545 391	273 412			
		E06-113	Cable, ac, 0 V to 600 V, above ground, no conduit, per 305 m (1000 ft)	33 286.3	4	0.000 120 170	72 896 904	2.50	0.05	0.08
		E06-121	Cable, ac, 0 V to 600 V, below ground, in duct, per 305 m (1000 ft)	40 000.4	5	0.000 124 999	70 080 730	16.40	0.73	2.79
		E06-122	Cable, ac, 0 V to 600 V, below ground, in conduit, per 305 m (1000 ft)	24 426.8	49	0.002 005 991	4 366 919	11.22	87.71	28.22
		E06-123	Cable, ac, 0 V to 600 V, below ground, insulated, per 305 m (1000 ft)	3095.3	80	0.025 845 534	338 937	7.60		7.60

		E06-211	Cable, ac, 601 kV to 15 kV, above ground, in conduit, per 305 m (1000 ft)	523 356.6	281	0.000 536 919	16 315 315	8.56	40.51	16.11
		E06-212[a]	Cable, ac, 601 kV to 15 kV, Above ground, in trays, per 305 m (1000 ft)	180.1	0	0.003 849 060	3 093 176			
		E06-214	Cable, ac, 601 kV to 15 kV, above ground, in trays, in conduit, per 305 m (1000 ft)	2646.0	2	0.000 755 852	11 589 564	4.00		4.00
		E06-221	Cable, ac, 601 kV to 15 kV, below ground, in conduit, per 305 m (1000 ft)	19 525.5	46	0.002 355 896	3 718 331	15.70	211.43	41.55
		E06-222	Cable, ac, 601 kV to 15 kV, below ground, in duct, per 305 m (1000 ft)	78.1	1	0.012 799 383	684 408			
		E06-223	Cable, ac, 601 kV to 15 kV, below ground, insulated, per 305 m (1000 ft)	22 770.3	454	0.019 938 292	439 356	5.13	3.97	4.01
	Aerial			37 500.3	439	0.011 706 565	748 298	2.03	0.35	1.91
		E07-200	Cable, aerial, > 15 kV, per 1.6 km (1 mile)	30 884.9	127	0.004 112 048	2 130 325	2.54	0.35	2.08
		E07-100	Cable, aerial, 0 kV to 15 kV, per 1.6 km (1 mile)	6615.5	312	0.047 162 173	185 742	1.82		1.82
	DC	E08-100	Cable, dc, insulated, per 305 m (1000 ft)	475.1	3	0.006 313 969	1 387 400	2.00		2.00
Cable connection	Underground	E05-100	Cable connection, underground, duct, ≤ 600 V	21 574.5	8	0.000 370 808	23 624 073	0.75		0.75
Capacitor bank	All types	E10-000	Capacitor/capacitor bank, all types	2041.1	104	0.050 951 857	171 927	2.37	4.27	3.13
Charger	Battery	E11-000	Charger, battery	666.0	26	0.039 040 966	224 380	7.46	0.72	2.29
Chiller				3607.7	1283	0.355 626 726	24 633	8.57	1.86	3.33
	Absorption	H10-100	Chiller, absorption	587.7	93	0.158 231 093	55 362	11.40	0.68	0.72
	Centrifugal			1054.5	529	0.501 674 408	17 462	7.73	11.29	24.68
		H10-210	Chiller, centrifugal, ≤ 600 tons (2110 kW)	152.1	298	1.959 149 120	4471	5.75	29.58	140.30
		H10-230	Chiller, centrifugal, > 1000 tons (3517 kW)	242.9	152	0.625 733 105	14 000	9.23	35.17	35.44

		H10-220	Chiller, centrifugal, 600 tons to 1000 tons (2110 kW to 3517 kW)	659.4	79	0.119 797 371	73 123	11.81	5.28	5.51
	Reciprocating			1193.5	192	0.160 868 248	54 455	10.77	1.65	2.21
		H10-321	Chiller, reciprocating, closed, with drive, 50 tons to 200 tons (176 kW to 703 kW)	881.8	139	0.157 633 096	55 572	11.11	1.53	2.06
		H10-331	Chiller, reciprocating, open, w/o drive, 50 tons to 200 tons (176 kW to 703 kW)	285.7	53	0.185 495 934	47 225	10.02	2.98	3.80
		H10-311[a]	Chiller, reciprocating, with drive, < 50 tons (176 kW)	26.0	0	0.026 651 082	446 729		1.00	1.00
	Rotary			122.5	15	0.122 477 741	71 523	7.33	8.47	9.47
		H10-420	Chiller, rotary, < 600 tons (2110 kW)	32.0	1	0.031 244 650	280 368	1.00	1.63	1.60
		H10-410	Chiller, rotary, 600 tons to 1000 tons (2110 kW to 3517 kW)	90.5	14	0.154 754 694	56 606	8.60	8.74	9.79
	Screw			649.5	454	0.698 994 807	12 532	7.83	8.12	10.69
		H10-510	Chiller, screw, ≤ 300 tons (1055 kW)	499.0	380	0.761 497 960	11 504	5.37	27.44	15.71
		H10-520	Chiller, screw, > 300 tons (1055 kW)	150.5	74	0.491 734 634	17 814	23.24	6.37	7.97
Circuit breaker				180 935.2	1437	0.007 942 070	1 102 987	15.11	7.99	11.33
	Air			9012.4	93	0.010 319 132	848 909	11.65	73.27	60.16
		E12-111	Circuit breaker, air, 3-phase, > 600 V, > 600 A, normally closed (NC)	8885.8	90	0.010 128 467	864 889	11.65	73.27	60.16
		E12-112	Circuit breaker, air, 3-phase, > 600 V, > 600 A, normally open (NO)	126.5	3	0.023 707 970	369 496			
	Fixed (includes molded case)			150 305.9	10	0.000 066 531	31 667 972	25.36	8.29	9.74
		E12-211	Circuit breaker, fixed (includes molded case), 3-phase, ≤ 600 V, ≤ 600 A, normally closed (NC)	34 569.2	4	0.000 115 710	75 706 529	23.25	3.09	9.64

		E12-212	Circuit breaker, fixed (includes molded case), 3-phase, ≤ 600 V, ≤ 600 A, normally open (NO)	26 607.0	3	0.000 112 752	77 692 576	18.67	8.61	8.73
		E12-221	Circuit breaker, fixed (includes molded case), 3-phase, ≤ 600 V, > 600 A, normally closed (NC)	88 546.5	1	0.000 011 294	75 667 016		13.62	13.62
		E12-222	Circuit breaker, fixed (includes molded case), 3-phase, ≤ 600 V, > 600 A, normally open (NO)	583.2	2	0.003 429 339	2 554 428	37.50	2.69	3.03
	Fixed (molded case)	E12-311	Circuit breaker, fixed (molded case), 600 V, single phase, normally closed (NC)	7027.5	1	0.000 142 299	61 560 528	1.00		1.00
	Metal clad (drawout)			9529.8	179	0.018 783 250	466 373	9.58	2.12	4.33
		E12-411	Circuit breaker, metal clad (drawout), ≤ 600 V, ≤ 600 A, normally closed (NC)	5705.6	18	0.003 154 788	2 776 732	6.50	2.02	2.02
		E12-412	Circuit breaker, metal clad (drawout), ≤ 600 V, ≤ 600 A, normally open (NO)	911.2	4	0.004 389 750	1 995 558	6.00	2.93	2.94
		E12-421	Circuit breaker, metal clad (drawout), ≤ 600 V, > 600 A, normally closed (NC)	2290.1	153	0.066 809 897	131 118	9.90	2.56	26.74
		E12-422	Circuit breaker, metal clad (drawout), ≤ 600 V, > 600 A, normally open (NO)	622.9	4	0.006 421 989	1 364 063	2.00	2.38	2.37
	Oil filled			1573.9	640	0.406 641 344	21 542	19.01	28.83	30.54
		E12-512	Circuit breaker, oil filled, > 5 kV, normally closed (NC)	1392.3	631	0.453 204 694	19 329	18.98	28.84	30.56
		E12-511	Circuit breaker, oil filled, > 5 kV, Normally open (NO)	181.6	9	0.049 569 941	176 720	23.75	8.00	20.60
	SF6 filled	E12-610	Circuit breaker, SF6 filled, normally closed (NC)	315.2	418	1.326 315 057	6605	12.81	51.03	42.52
	Vacuum			3170.7	96	0.030 277 684	289 322	10.71	0.61	2.91
		E12-711	Circuit breaker, vacuum, < 15 kV, < 600 A, normally closed (NC)	514.4	3	0.005 832 348	1 501 968	5.33	0.05	0.06

		E12-712[a]	Circuit breaker, vacuum, < 15 kV, < 600 A, normally closed (NC)	458.2	0	0.001 512 626	7 870 965		1.84	1.84
		E12-721	Circuit breaker, vacuum, < 15 kV, > 600 A, normally closed (NC)	1476.2	65	0.044 031 239	198 950	11.58	2.60	14.89
		E12-722	Circuit breaker, vacuum, < 15 kV, > 600 A, normally closed (NC)	716.8	28	0.039 061 903	224 259	9.39	0.35	0.49
		E12-730[a]	Circuit breaker, vacuum, > 15 kV	5.0	0	0.138 553 516	85 929			
Compressor	Refrigerant			1344.2	19	0.014 134 513	619 760	8.69	0.93	1.02
		H11-010	Compressor, refrigerant, ≤ 1 ton (3.52 kW)	74.7	2	0.026 780 146	327 108	9.00	1.31	1.53
		H11-020	Compressor, refrigerant, > 1 ton (3.52 kW)	1052.0	5	0.004 752 765	1 843 138	3.50	0.91	0.93
		H11-100	Compressor, refrigerant, screw	217.5	12	0.055 165 812	158 794	10.83	0.94	1.15
Computer				406.3	100	0.246 142 641	35 589	4.30	4.82	23.48
	Control system server	C02-200	Computer, control system server	156.9	94	0.598 997 888	14 624	4.52	4.65	27.62
	Personal computer (PC) workstation	C02-100	Computer, PC workstation	249.3	6	0.024 063 554	364 036	1.90	5.09	4.09
Condenser				3972.6	305	0.076 775 438	114 099	8.10	2.83	4.91
	Double tube	H12-100	Condensers, double tube	298.7	8	0.026 781 865	327 087	2.50	2.63	2.63
	Propeller type fans/coils	H12-200	Condensers, propeller type fans with coils, direct expansion (DX)	2097.2	267	0.127 309 780	68 809	8.18	1.98	4.91
	Shell and tube	H12-300	Condenser, shell and tube	1576.7	30	0.019 027 462	460 387	9.50	6.86	7.06
Control center	Motor/load center	C03-100	Control center, motor/load center	1109.4	12	0.010 816 417	809 880	5.03	6.40	6.38
Control panel				6247.8	73	0.011 684 020	749 742	2.86	4.29	4.36
	Generator	C04-100	Control panel, generator, w/o switchgear	1808.4	30	0.016 589 350	528 050	4.38	0.62	1.45
	Heating, ventilation, and air conditioning (HVAC)/chillers/air-handling unit (AHU)	C04-200	Control panel, HVAC/chillers/AHU, w/o switchgear	3841.9	32	0.008 329 286	1 051 711	2.07	1.41	1.45
	Switchgear controls	C04-300	Control panel, switchgear controls	597.6	11	0.018 407 130	475 903	1.27	7.01	6.96

Control system				605.1	385	0.636 294 482	13 767	5.35	0.92	1.68
	≤ 1000 acquisition points	C12-100	Control system, ≤ 1000 acquisition points	384.7	99	0.257 318 645	34 043	1.73	1.26	1.43
	> 1000 acquisition points	C12-200	Control system, > 1000 acquisition points	220.3	286	1.298 060 184	6749	6.75	0.88	1.72
Convector	Fin tube baseboard			6387.9	8	0.001 252 62	6 994 782	2.44	0.13	0.15
		H13-110	Convector, fin tube baseboard, electric	1519.8	8	0.005 263 936	1 664 154	2.44	0.33	0.43
		H13-120[a]	Convector, fin tube baseboard, steam or hot water	4868.2	0	0.000 142 384	83617694		0.08	0.08
Cooling tower				2063.7	556	0.269 418 665	32514	13.56	1.50	2.24
	Atmospheric type (w/o fans)	H14-100	Cooling tower, atmospheric type (w/o fans, motors, and internal lift pump)	323.7	24	0.074 137 736	118158	88.92	0.99	1.14
	Atmospheric type (with fans)	H14-300	Cooling tower, atmospheric type (with fans, motors, and internal lift pump)	1037.4	502	0.483 905 897	18103	8.77	4.34	8.28
	Evaporative type (w/o fans)	H14-200	Cooling tower, evaporative type (w/o fans, motors, and internal lift pump)	515.3	3	0.005 821 372	1 504 800	16.67	1.44	1.46
	Evaporative type (with fans)	H14-400	Cooling tower, evaporative type (with fans, motors, and internal lift pump)	187.2	27	0.144 194 894	60 751	6.25	3.83	4.78
Damper assembly				18 711.9	74	0.003 954 699	2 215 086	23.10	0.07	0.65
	Motor operated	H15-100	Damper assembly, motor operated	15 793.2	48	0.003 039 287	2 882 255	28.73	0.07	0.54
	Pneumatically operated	H15-200	Damper assembly pneumatically operated	2918.7	26	0.008 907 946	983 392	11.83	4.00	59.87
Dehumidifier	> 10 lb/h (4.54 kg/h)	H16-100	Dehumidifier, > 4.54 kg/h (10 lb/h)	98.3	68	0.691 808 122	12 662	16.26	17.27	32.31
Direct fired furnace				1301.1	404	0.310 517 283	28 211	3.64	13.86	23.35
	≤ 500 MB/h	H17-100	Direct fired furnace, ≤ 500 MBH (147 kW)	161.4	6	0.037 173 459	235 652	0.83	3.33	3.82
	> 500 MB/h	H17-200	Direct fired furnace, >500 MBH (147 kW)	1139.6	398	0.349 230 237	25 084	3.67	15.69	24.90
Distribution panel				7939.1	31	0.003 904 724	2 243 436	20.86	3.4	11.70

	≤ 225 A	E13-100	Distribution panel, ≤ 225 A, circuit breakers, not included (wall mount unit)	6552.6	25	0.003 815 271	2 296 036	22.69	1.41	10.90
	> 225 A	E13-200	Distribution panel, > 225 A, circuit breakers, not included (wall mount unit)	1386.5	6	0.004 327 482	2 024 272	16.00	10.06	14.34
Drive				4534.9	169	0.037 266 634	235 063	13.08	2.15	14.04
	Adjustable speed	E14-100	Drive, adjustable speed	3158.4	96	0.030 395 480	288 201	15.51	3.45	22.10
	Variable frequency	E14-200	Drive, variable frequency	1376.5	73	0.053 032 158	165 183	9.07	1.28	7.59
Engine				1245.6	2007	1.611 246 868	5437	1.36	2.87	2.71
	Diesel	E15-100	Engine, diesel	207.2	134	0.646 760 906	13 544	9.64	3.27	4.11
	Gas	E15-200	Engine, gas	1038.4	1873	1.803 679 412	4857	1.00	0.75	0.94
Evaporator	Coil			8150.2	40	0.004 907 850	1 784 896	13.03	0.27	0.29
		H18-100	Evaporator, direct expansion, coil	7114.1	31	0.004 357 533	2 010 312	14.55	0.27	0.29
		H18-120	Evaporator, direct expansion, shell tube	1036.1	9	0.008 686 501	1 008 461	5.17	0.28	0.30
Fan				19 708.4	1549	0.078 595 830	111 456	10.70	2.09	3.71
	Centrifugal	H19-100	Fan, centrifugal	11 895.7	577	0.048 504 894	180 600	10.51	1.71	3.57
	Propeller/disc	H19-200	Fan, propeller/disc	3857.7	649	0.168 236 811	52 069	10.88	2.09	4.37
	Tubeaxial	H19-300	Fan, tubeaxial	2244.8	69	0.030 737 667	284 992	5.51	4.04	4.09
	Vaneaxial	H19-400	Fan, vaneaxial	1710.3	254	0.148 515 645	58 984	14.24	1.10	1.61
Filter				5796.7	33	0.005 692 936	1 538 749	11.66	0.30	0.36
	Electrical	E16-200[a]	Filter, electrical, tempest	342.1	0	0.002 026 405	5 875 341			
	Mechanical			5454.6	33	0.006 049 940	1 447 948	11.66	0.30	0.36
		H20-100	Filter, mechanical, air regulator set	3314.5	22	0.006 637 450	1 319 784	15.33	0.05	0.08
		H20-200[a]	Filter, mechanical, fuel oil	743.2	0	0.000 932 659	12 765 459		0.49	0.49
		H20-300	Filter, mechanical, lube oil	1396.9	11	0.007 874 695	1 112 424	3.95	1.47	1.72
Fuse				10 226.0	483	0.047 232 405	185 466	4.00		4.00
	> 15 kV	E17-300	Fuse, > 15 kV	4756.7	483	0.101 541 423	86 270	4.00		4.00
	> 5 kV ≤ 15 kV	E17-200[a]	Fuse, > 5 kV ≤ 15 kV	3590.5	0	0.000 193 050	61 672 329			
	0 kV to 5 kV	E17-100[a]	Fuse, 0 kV to 5 kV	1878.8	0	0.000 368 923	32 271 812			
Gauge	Fluid level	C05-100	Gauge, fluid level	830.2	4	0.004 817 989	1 818 186	3.31	7.13	6.04
Generator				4538.6	2283	0.503 018 519	17 415	23.24	2.93	3.93

	Diesel engine			3045.1	1305	0.428 550 581	20 441	19.29	2.02	3.08
		E18-111	Generator, diesel engine, packaged, < 250 kW, continuous	15.0	16	1.063 558 550	8 237			
		E18-112	Generator, diesel engine, packaged, < 250 kW, standby	857.8	281	0.327 590 557	26 741	12.24	1.69	4.88
		E18-121	Generator, diesel engine, packaged, 250 kW to 1.5 MW, continuous	266.0	155	0.582 686 262	15 034	25.74	0.52	1.15
		E18-122	Generator, diesel engine, packaged, 250 kW to 1.5 MW, standby	1439.8	358	0.248 652 553	35 230	12.95	1.72	2.63
		E18-211	Generator, diesel engine, unpackaged, 750 kW to 7 MW, continuous	180.6	328	1.815 727 611	4825	25.08	3.86	5.00
		E18-212	Generator, diesel engine, unpackaged, 750 kW to 7 MW, standby	285.9	167	0.584 093 735	14 998	23.91	2.57	3.11
	Gas turbine			983.7	485	0.493 016 528	17 768	25.05	2.39	2.72
		E19-111	Generator, gas turbine, packaged, 750 kW to 7 MW, continuous	185.5	295	1.590 684 138	5507	27.31	0.83	1.23
		E19-112	Generator, gas turbine, packaged, 750 kW to 7 MW, standby	612.4	113	0.184 526 491	47 473	6.05	4.40	4.42
		E19-211	Generator, gas turbine, unpackaged, 750 kW to 7 MW, continuous	185.9	77	0.414 185 923	21 150	50.33	13.26	15.87
	Hydro turbine	E20-000	Generator, hydro turbine	90.4	27	0.298 790 286	29 318	78.36	238.44	310.21
	Natural gas			281.4	250	0.888 285 342	9862	5.87	139.75	64.13
		E21-110	Generator, natural gas, < 250 kW, continuous	7.4	5	0.674 926 036	12 979	1.50		1.50
		E21-120	Generator, natural gas, < 250 kW, standby	222.4	31	0.139 419 404	62 832	6.33	32.87	34.60
		e21-210	generator, natural gas, ≥ 250 kW, continuous	51.7	214	4.140 691 264	2116		191.73	71.13
	Steam	E23-000	Generator, steam, heat recovery	20.5	86	4.185 891 452	2093	162.40		45.84
	Steam turbine	E22-000	Generator, steam turbine	117.4	130	1.107 687 280	7908	100.59	288.24	263.61
Heat exchanger				4858.5	272	0.055 984 436	156 472	10.81	1.11	1.74

	Boiler system	H21-100	Heat exchanger, boiler system, steam	964.0	164	0.170 129 316	51 490	7.22	18.15	19.15
	Lube oil	H21-200	Heat exchanger, lube oil	546.2	15	0.027 462 330	318 982	12.21	6.52	14.46
	Radiator	H21-310	Heat exchanger, radiator, small tube	1801.7	65	0.036 076 572	242 817	12.55	0.23	0.60
	Water to water	H21-400	Heat exchanger, water to water	1546.6	28	0.018 104 293	483 863	10.10	0.38	0.86
Heat pump	All types	H22-000	Heat pump	1330.4	82	0.061 635 471	142 126	3.26	0.76	6.37
Heater	Lube/fuel oil or jacket water	E24-110	Heater, lube/fuel oil or jacket water, electric	768.1	62	0.080 713 618	108 532	3.13	1.21	1.28
Humidifier	All types	H23-000	Humidifier	1569.1	38	0.024 217 472	361 722	4.11	1.86	2.00
Humistat assembly	All types	H24-000	Humistat assembly	643.3	10	0.015 544 284	563 551	1.00		1.00
Inverter	All types	E25-000	Inverter, all types	612.1	38	0.062 079 275	141 110	17.45	3.93	7.59
Line conditioner	All types	E26-000[a]	Line conditioner, all types	10.7	0	0.064 971 423	183 247			
Meter				18 288.1	26	0.001 421 689	6 161 684	38.78	0.38	1.80
	Electric	C06-100	Meter, electric	15 067.2	7	0.000 464 587	18 855 470	1.29	3.29	3.10
	Fuel	C06-200	Meter, fuel	238.2	13	0.054 567 200	160 536	72.00		72.00
	Water	C06-300	Meter, water	2982.7	6	0.002 011 594	4 354 756	4.75	0.01	0.04
Motor	Electric			33 939.9	567	0.016 705 988	524 363	29.11	1.09	3.59
		E29-100	Motor, electric, dc	1513.9	119	0.078 605 141	111 443	67.60	0.42	0.97
		E29-210	Motor, electric, induction, ≤ 600 V	3195.9	340	0.106 385 715	82 342	21.50	14.55	53.01
		E29-220	Motor, electric, induction, > 600 V	429.9	11	0.025 584 819	342 391	4.44	3.29	3.31
		E29-310[a]	Motor, electric, single phase, ≤ 5 A	25 377.5	0	0.000 027 314	435 895 106		0.49	0.49
		E29-320	Motor, electric, single phase, >5 A	1455.1	1	0.000 687 237	12 746 688	3.00	0.71	0.72
		E29-410	Motor, electric, synchronous, ≤ 600 V	1726.6	94	0.054 441 911	160 905	7.34	1.77	6.37
		E29-420	Motor, electric, synchronous, > 600 V	241.0	2	0.008 298 661	1 055 592	36.00	3.00	4.65
Motor generator set	3 phase			509.9	23	0.045 104 339	194 216	6.71	0.84	0.84
		E27-120	Motor generator set, 3 phase, 400 Hz	202.6	1	0.004 937 036	1 774 344	8.00	2.87	2.89

		E27-110	Motor generator set, 3 phase, 60 Hz	307.4	22	0.071 573 093	122 392	6.62	0.82	0.83
Motor starter				4056.8	33	0.008 134 545	1 076 889	4.33	0.62	1.34
	≤ 600 V	E28-100	Motor starter, ≤ 600 V	3505.6	28	0.007 987 258	1 096 747	3.37	0.72	1.66
	> 600 V	E28-200	Motor starter, > 600 V	551.2	5	0.009 071 298	965 683	9.15	0.48	0.87
Network hub				234.0	2	0.008 545 408	1 025 112	2.75		2.75
	Ethernet	C07-100	Network hub, Ethernet	229.0	2	0.008 732 057	1 003 200	2.75		2.75
	Fiber-optic	C07-200[a]	Network hub, fiber-optic	5.0	0	0.138 553 516	85 929			
Network printer				13 311.4	4682	0.351 727 580	24 906	1.69	1.55	3.29
	Inkjet	NWP-100	Network printer, inkjet	1260.0	670	0.531 744 876	16 474	1.74	1.78	5.57
	Laser	NWP-200	Network printer, laser	12 051.4	4012	0.332 906 396	26 314	1.68	1.50	2.87
Oil cooler	All types	E30-000	Oil cooler	92.9	3	0.032 302 791	271 184	13.25	0.50	2.20
Pipe				14 886.9	22	0.001 477 814	5 927 674	8.38	7.72	7.72
	Flex			1818.8	10	0.005 498 167	1 593 258	3.38	4.00	3.50
		H25-112	Pipe, flex, non-reinforced, > 100 mm (4 in)	206.3	3	0.014 544 485	602 290	3.33	4.00	3.60
		H25-111	Pipe, flex, reinforced, < 100 mm (4 in)	273.8	3	0.010 957 670	799 440	8.00		8.00
		H25-122	Pipe, flex, reinforced, > 100 mm (4 in)	1338.7	4	0.002 987 876	2 931 848	2.25		2.25
	Refrigerant			11 221.0	6	0.000 534 713	16 382 612	9.33	3.06	3.20
		H25-310	Pipe, refrigerant, < 25 mm per 30.5 m (1 in per 100 ft)	7913.6	3	0.000 379 094	23 107 704	10.67	2.00	2.11
		H25-320	Pipe, refrigerant, 25 mm to 80 mm per 30.5 m (1 in to 3 in per 100 ft)	3307.4	3	0.000 907 065	9 657 520	8.00	8.78	8.73
	Water			1847.1	6	0.003 248 338	2 696 764	14.08	8.00	8.01
		H25-410[a]	Pipe, water, ≤ 50 mm per 30.5 m (2 in per 100 ft)	462.5	0	0.001 498 852	7 943 294			
		H25-450[a]	Pipe, water, > 300 mm per 30.5 m (12 in per 100 ft)	8.2	0	0.084 984 454	140 094			
		H25-420	Pipe, water, 50 mm to 100 mm per 30.5 m (2 in to ≤ 4 in per 100 ft)	292.3	6	0.020 530 031	426 692	14.08		14.08
		H25-430[a]	Pipe, water, 100 mm to 200 mm per 30.5 m (4 in to 8 in per 100 ft)	268.7	0	0.002 579 961	4 614 729			

		H25-440[a]	Pipe, water, 200 mm to 300 mm per 30.5 m (8 in to 12 in per 100 ft)	815.6	0	0.000 849 893	14 008 612		8.00	8.00
Pressure control assembly	All types	C08-000	Pressure control assembly	896.3	82	0.091 485 687	95 753	8.10	3.53	4.08
Pressure regulator	Hot gas	C09-100	Pressure regulator, hot gas	2711.4	29	0.010695434	819 041	2.94	1.68	19.52
Programmable logic controller	All types	C10-000	Programmable logic controller (PLC)	203.9	6	0.029 422 829	297 728	23.50	2.00	73.27
Pump				25 386.6	3097	0.121 993 479	71 807	11.83	1.75	6.24
	Centrifugal			23 888.4	2917	0.122 109 700	71 739	11.91	1.92	6.47
		H26-110	Pump, centrifugal, with drive	21 835.4	2655	0.121 591 798	72 045	11.95	2.21	7.95
		H26-120	Pump, centrifugal, w/o drive	2052.9	262	0.127 621 356	68 641	11.28	1.04	1.52
	Positive displacement	H26-200	Pump, positive displacement	1498.2	180	0.120 140 438	72 915	7.91	0.70	4.74
Recloser (interrupter)				8368.5	85	0.010 157 168	862 445	5.00	6.02	5.97
	Electronic	E31-100	Recloser (interrupter), electronic	1949.4	13	0.006 668 840	1 313 572			
	Hydraulic	E31-200	Recloser (interrupter), hydraulic	2939.1	58	0.019 734 144	443 901		8.00	8.00
	Undefined type	E31-099[a]	Recloser (interrupter), undefined type	3480.0	14	0.004 022 941	2 177 511	5.00	5.00	5.00
Rectifiers	All types	E32-000	Rectifiers, all types	563.4	2	0.003 549 686	2 467 824	16.00	3.45	3.47
Relay	Electromechanical			5307.4	5	0.000 942 089	9 298 488	26.33	3.63	3.70
		E33-110	Relay, electromechanical, differential, differential voltage	828.1	2	0.002 415 059	3 627 240	35.50	4.28	4.51
		E33-120[a]	Relay, electromechanical, drawout	790.4	0	0.000 876 976	13 576 000			
		E33-130	Relay, electromechanical, overcurrent	3688.8	3	0.000 813 265	10 771 400	8.00	3.35	3.36
Router	Wired	RTR-100	Router, wired	2763.5	262	0.094 806 605	92 399	2.14	1.13	3.37
Sending unit				43 914.1	171	0.003 893 968	2 249 633	6.39	0.07	1.56
	Air velocity	C13-100	Sending unit, air velocity	7492.2	47	0.006 273 186	1 396 420	6.96	0.04	1.30
	Pressure	C13-200	Sending unit, pressure	7565.9	95	0.012 556 363	697 654	5.82	0.10	2.22
	Temperature	C13-300	Sending unit, temperature	28 856.0	29	0.001 004 991	8 716 496		0.25	0.39
Server				8145.9	540	0.066 290 672	132 145	3.02	1.00	2.41

	Blade	SVR-100	Server, blade	526.0	25	0.047 528 517	18 310	2.68	0.70	2.29
	Rack mount	SVR-200	Server, rack mount	6323.2	387	0.061 203 480	143 129	3.02	0.98	2.38
	Tower case	SVR-300	Server, tower case	1296.8	128	0.0987 065 589	88 748	3.08	1.09	2.49
Strainer				9788.4	88	0.008 990 193	974 395	16.96	0.35	0.62
	Air or gaseous	H27-110	Strainer, air or gaseous, air systems	304.2	1	0.003 287 222	266 4864			
	Liquid			9484.2	87	0.009 173 117	954 964	16.96	0.35	0.62
		H27-210[a]	Strainer, liquid, coolant	488.2	0	0.001 419 921	8 384 847		1.62	1.62
		H27-220[a]	Strainer, duplex fuel/lube oil	280.2	0	0.002 473 565	4 813 224		0.86	0.86
		H27-230[a]	Strainer, liquid, fuel oil	460.4	0	0.001 505 416	7 908 659		1.67	1.67
		H27-240	Strainer, liquid, lube oil	1161.2	25	0.021 528 741	406 898	14.29	1.85	4.12
		H27-251	Strainer, water, ≤ 100 mm (4 in)	6466.1	25	0.003 866 327	2 265 716	2.25	0.00	0.00
		H27-252	Strainer, water, > 100 mm (4 in)	628.1	37	0.058 908 203	148 706	25.58	4.03	8.99
Switch				36 667.8	385	0.010 499 665	834 312	8.63	2.01	7.08
	Automatic transfer			2883.7	101	0.035 024 398	250 111	7.89	2.40	2.96
		E34-110	Switch, automatic transfer, ≤ 600 V, > 600 A	1030.8	27	0.026 193 875	334 429	2.66	8.98	8.32
		E34-120	Switch, automatic transfer, ≤ 600 V, 0 A to 600 A	1852.9	74	0.039 936 775	219 347	9.90	1.82	2.42
	Disconnect			19 349.5	23	0.001 188 660	7 369 646	17.83	1.75	1.90
		E34-211	Switch, disconnect, enclosed, ≤ 600 V	8372.7	6	0.000 716 616	12 224 124		2.09	2.09
		E34-212	Switch, disconnect, enclosed, > 600 V to ≤ 5 kV	2238.8	2	0.000 893 351	9 805 776	46.00	3.03	3.38
		E34-213	Switch, disconnect, enclosed, > 5 kV	2091.2	15	0.007 172 820	1 221 277	15.82	2.08	2.86
		E34-222[a]	Switch, disconnect, fused, dc, > 600 A; ≤ 600 V	861.5	0	0.000 804 591	14 797 365			
		E34-221[a]	Switch, disconnect, fused, dc, ≤ 600 A; ≤ 600 V	5785.4	0	0.000 119 811	99 372 047		0.54	0.54
	Electric	E34-310	Switch, electric, on/off breaker type, non-knife, ≤ 600 V	3115.2	2	0.000 642 008	13 644 684	1.00	0.01	0.01
	Float	E34-400	Switch, float, electric	2513.6	87	0.034 611 071	253 098	9.84	0.91	22.86
	Manual transfer			640.4	0	0.001 082 408	10 999 388			

		E34-510[a]	Switch, manual transfer, ≤ 600 V, ≤ 600 A	266.6	0	0.002 599 818	4 579 482			
		E34-520[a]	Switch, manual transfer, ≤ 600 V, > 600 A	373.8	0	0.001 854 517	6 419 906			
	Oil filled	E34-610[a]	Switch, oil filled, ≥ 5 kV	300.2	0	0.002 308 614	5 157 129		1.38	1.38
	Pressure	E34-700	Switch, pressure	6661.0	169	0.025 371 639	345 267	7.04	3.08	16.89
	Static			921.5	2	0.002 170 468	4 035 996	13.00	2.04	2.11
		E34-810[a]	Switch, static, ≤ 600 V, 0 A to 600 A	498.4	0	0.001 390 875	8 559 953		0.03	0.03
		E34-820	Switch, static, ≤ 600 V, > 600 A ≤ 1000 A	130.0	1	0.007 692 794	1 138 728	2.00	0.05	0.08
		E34-830	Switch, static, ≤ 600 V, > 1000 A	271.7	1	0.003 680 066	2 380 392	24.00	3.47	3.58
		E34-850[a]	Switch, static, with insulated-gate bipolar transistor (IGBT) technology	15.3	0	0.045 210 636	26 3341			
		E34-860[a]	Switch, static, w/o IGBT technology	6.0	0	0.114 582 754	103 906			
	Vibration	E34-900	Switch, vibration	282.7	1	0.003 537 644	2 476 224		0.50	0.50
Switchgear				6747.6	47	0.006 965 393	1 257 646	24.32	3.35	3.56
	Bare bus			4229.7	42	0.009 929 718	882 200	24.31	3.64	3.94
		E36-110	Switchgear, bare bus, ≤ 600 V (circuit breaker not included)	2493.6	23	0.009 223 683	949 729	7.91	4.28	4.35
		E36-130	Switchgear, bare bus, > 5 kV (circuit breaker not included)	895.7	15	0.016 746 168	523 105	2.27	1.28	1.30
		E36-120	Switchgear, bare bus, > 600 V to ≤ 5 kV (circuit breaker not included)	840.4	4	0.004 759 530	1 840 518	195.75	6.59	9.67
	Insulated bus			1713.6	5	0.002 917 820	3 002 242	24.40	2.90	2.97
		E36-210[a]	Switchgear, insulated bus, ≤ 600 V (circuit breaker not included)	505.2	0	0.001 372 077	8 677 224		3.18	3.18
		E36-220	Switchgear, insulated bus, > 600 V to ≤ 5 kV (circuit breaker not included)	405.8	2	0.004 928 902	1 777 272	5.00	0.77	0.78
		E36-230	Switchgear, insulated bus, > 5 kV (circuit breaker not included)	802.7	3	0.003 737 584	2 343 760	37.33	14.01	14.43

	Load center (free standing unit)	E36-300[a]	Switchgear, load center (free standing unit)	804.3	0	0.000 861 792	13 815 200		0.59	0.59
Tank				4876.1	137	0.028 096 327	311 785	18.02	1.11	3.10
	Air	E37-110	Tank, air, receiver	1519.1	22	0.014 482 011	604 888	11.53	1.25	1.63
	Liquid			3357.0	115	0.034 257 224	255 712	18.99	0.88	5.31
		E37-210	Tank, liquid, day, fuel	484.8	2	0.004 125 040	2 123 616	5.00	0.31	0.35
		E37-220	Tank, liquid, fuel	614.7	21	0.034 162 930	256 418	13.80	1.28	2.52
		E37-230	Tank, liquid, water	2257.4	92	0.040 754 653	214 945	20.57	0.91	7.23
Thermocouple	All types	C14-000	Thermocouple	5761.5	101	0.017 530 270	499 707	13.48	14.00	479.86
Thermostat	Radiator	C15-100	Thermostat, radiator	8735.0	153	0.017 515 835	500 119	3.16	1.13	2.00
Transducer				26 305.4	81	0.003 079 211	2 844 885	3.74	0.06	0.09
	Flow	C16-100	Transducer, flow	1188.0	5	0.004 208 706	2 081 400	2.00	1.17	1.18
	Pressure	C16-200	Transducer, pressure	2139.0	28	0.013 090 212	669 202	7.50	2.28	3.07
	Temperature	C16-300	Transducer, temperature	22 978.4	48	0.002 088 916	4 193 563	1.89	0.02	0.03
Transformer				164 239.4	456	0.002 776 435	3 155 125	14.92	10.83	11.43
	Dry			96 735.4	248	0.002 563 695	3 416 944	3.63	2.77	3.40
		E38-111	Transformer, dry, air cooled, ≤ 500 kVA	86095.4	226	0.002 624 996	3 337 148	2.13	2.36	2.33
		E38-112	Transformer, dry, air cooled, > 500 kVA ≤ 1500 kVA	1700.3	3	0.001 764 436	4 964 760	2.00	5.41	36.50
		E38-113[a]	Transformer, dry, air cooled, > 1500 kVA ≤ 3000 kVA	999.7	0	0.000 693 337	17 171 772		4.39	4.39
		E38-114[a]	Transformer, dry, air cooled, > 3000 kVA ≤ 5000 kVA	1142.2	0	0.000 606 854	19 618 918		5.50	5.50
		E38-121	Transformer, dry, isolation, delta wye, < 600 V	6797.8	19	0.002 795 011	3 134 156	21.26	0.93	2.52
	Liquid			67 504.0	208	0.00 3081 299	2 842 957	36.89	13.29	14.16
		E38-211	Transformer, liquid, forced air, ≤ 5000 kVA	5849.5	52	0.008 889 630	985 418	8.69	0.98	2.08
		E38-212	Transformer, liquid, forced air, > 5000 kVA ≤ 10 000	600.6	23	0.038 292 418	228 766	251.00	22.96	23.60
		E38-213	Transformer, liquid, forced air, >10 000 kVA ≤ 50 000 kVA	482.1	34	0.070 518 976	124 222	965.33	21.69	24.34
		E38-214	Transformer, liquid, forced air, > 50 000	18.6	24	1.289 752 650	6792	11.95	2.43	5.30
		E38-221	Transformer, liquid, non-forced air, ≤ 3000 kVA	59 708.0	63	0.001 055 134	8 302 262	2.33	2.00	2.02

		E38-222	Transformer, liquid, non-forced air, > 3000 kVA ≤ 10 000 kVA	190.7	1	0.005 242 671	1 670 904	1.00	2.67	2.50
		E38-223	Transformer, liquid, non-forced air, > 10 000 kVA ≤ 50 000 kVA	654.3	11	0.016 811 614	521 068	6.09	0.58	0.65
UPS				1232.8	65	0.052 726 440	166 141	5.24	2.08	6.48
	Rotary	E39-100	Uninterruptible power supply (UPS), rotary	134.7	2	0.014 848 263	589 968	8.75	6.11	7.81
	Small computer room floor	E39-200	Uninterruptible power supply (UPS), small computer room floor	724.7	41	0.056 575 669	154 837	6.25	2.12	3.74
	Solid state			373.4	22	0.058 919 780	148 677	2.93	1.14	11.44
		E39-310	Uninterruptible power supply (UPS), solid state, 60 Hz/module	357.3	22	0.061 578 810	142 257	2.93	1.09	13.83
		E39-320[a]	Uninterruptible power supply (UPS), solid state, with IGBT technology	16.1	0	0.042 990 437	276 941		1.30	1.30
Valve				157 135.7	1345	0.008 559 481	1 023 427	11.94	2.62	8.08
	3-way			16 490.6	7	0.000 424 484	20 636 822	5.86	0.52	0.81
		H28-110	Valve, 3-way, diverting/sequencing	736.9	4	0.005 428 034	1 613 844	9.13	0.02	0.59
		H28-120	Valve, 3-way, mixing control	15 753.7	3	0.000 190 432	46 000 792	1.50	1.02	1.03
	Backflow preventer	H28-200	Valve, backflow preventer	742.6	30	0.040 401 283	216 825	13.27	1.11	15.63
	Ball			2703.6	5	0.001 849 362	4 736 770	1.20	0.19	0.24
		H28-310[a]	Valve, ball, normally closed (NC)	1092.7	0	0.000 634 368	18 768 000		0.19	0.19
		H28-320	Valve, ball, normally open (NO)	1611.0	5	0.003 103 705	2 822 434	1.20		1.20
	Butterfly			18 225.8	26	0.001 426 553	6 140 677	3.88	0.55	0.67
		H28-410	Valve, butterfly, normally closed (NC)	2809.7	26	0.009 253 770	946 641	3.88	1.01	1.67
		H28-420[a]	Valve, butterfly, normally open (NO)	15 416.1	0	0.000 044 963	64 793 976		0.48	0.48
	Check	H28-500	Valve, check	4699.2	44	0.009 363 323	935 565	26.69	1.11	8.60
	Control			22 796.4	647	0.028 381 678	308 650	17.32	0.50	15.34
		H28-610	Valve, control, normally closed (NC)	17 563.1	388	0.022 091 808	396 527	17.76	0.23	8.54

		H28-620	Valve, control, normally open (NO)	5233.3	259	0.049 490 515	177 004	16.93	1.56	38.85
	Expansion	H28-700[a]	Valve, expansion	1984.1	0	0.000 349 348	34 080 094			
	Gate			19 302.5	97	0.005 025 268	1 743 191	10.45	0.81	33.26
		H28-830	Valve, gate, double flap	173.2	76	0.438 785 195	19 964	10.67		10.67
		H28-810	Valve, gate, normally closed (NC)	1830.5	8	0.004 370 485	2 004 354	7.50	0.59	0.99
		H28-820	Valve, gate, normally open (NO)	17 298.8	13	0.000 751 498	11 656 721	9.31	1.30	150.13
	Globe			41 402.3	66	0.001 594 112	5 495 221	16.65	1.00	1.74
		H28-910[a]	Valve, globe, normally closed (NC)	22 125.4	0	0.000 031 328	80 035 718		1.00	1.00
		H28-920	Valve, globe, normally open (NO)	19 277.0	66	0.003 423 773	2 558 581	16.65	0.40	129.72
	Plug			15 233.3	148	0.009 715 539	901 648	1.81	0.05	1.59
		H28-A10	Valve, plug, normally closed (NC)	8845.9	123	0.013 904 727	630 002	1.37	0.05	1.17
		H28-A20	Valve, plug, normally open (NO)	6387.4	25	0.003 913 946	2 238 151	4.00		4.00
	Reducing	H28-B10	Valve, reducing, makeup water	701.9	100	0.142 473 496	61 485	5.56	0.59	17.99
	Relief	H28-C00	Valve, relief	10 598.4	165	0.015 568 452	562 676	7.55	102.91	137.61
	Suction	H28-D00	Valve, suction	2255.1	10	0.004 434 439	1 975 447	7.25	0.61	0.77
Valve operator				10 025.1	80	0.007 980 004	1 097 744	10.02	1.06	1.47
	Electric	C17-100	Valve operator, electric	3684.0	43	0.011 672 052	750 511	16.42	0.98	1.40
	Hydraulic	C17-200	Valve operator, hydraulic	68.2	6	0.087 937 681	99 616	3.00	2.16	2.20
	Pneumatic	C17-300	Valve operator, pneumatic	6272.8	31	0.004 941 961	1 772 576	2.92	0.98	1.76
Voltage regulator	Static	E40-100	Voltage regulator, static	3381.5	77	0.022 771 080	384 698	15.73	0.53	2.23
Water cooling coil	Fan coil unit	H29-100	Water cooling coil, fan coil unit	16 076.0	96	0.005 971 646	1 466 932	3.72	2.04	2.09
Water heater	Domestic hot water			1399.8	44	0.031 431 955	278 697	6.37	1.28	12.85
		H30-110	Water heater, domestic hot water, electric	957.5	19	0.019 843 370	441 457	9.64	0.82	29.64
		H30-130	Water heater, domestic hot water, gas	442.4	25	0.056 516 246	155 000	3.53	1.35	9.11
Workstation	All types	WST-000	Workstation	169 635.1	7948	0.046 853 516	186 966	0.73	0.62	1.11

[a] Failure rate calculated using 50% single-sided confidence interval.Part 2: Equipment reliability surveys conducted between 1976 and 1994.

5.3 Introduction

Clause 6 presents data derived from a series of electrical equipment surveys for specific types of equipment according to Table 3.

Table 3—Part 2 equipment reliability table reference guide

Electrical equipment types		Reference tables in Part 2: survey data from 1976 to 1989
Motors	> 50 hp (37.3 kW)	Table 23, Table 25
	> 200 hp (149 kW)	Table 16, Table 17, Table 18, Table 19, Table 20, Table 21, Table 22
	> 250 hp (187 kW)	Table 26
Generators		Table 5
Transformers	Power	Table 6, Table 8, Table 9, Table 10, Table 11, Table 12, Table 13, Table 14
	Rectifier	Table 7, Table 9, Table 10, Table 11, Table 12, Table 13, Table 15
Switchgear	Bus insulated	Table 4
	Bus bare	Table 4

5.4 1979 switchgear bus reliability data

The reliability of switchgear bus in industrial and commercial applications was investigated in a 1979 survey (see O'Donnell [B29] and *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 100) and the summarized failure rate and median outage duration time for the various subcategories of equipment are shown in Table 4. In this survey, the term *units* for a bus is defined as the total number of connected circuit breakers and connected switches. In the previous survey of 1974, the term *units* included the total number of connected circuit breakers or instrument transformer compartments. The total number of plants in the 1979 survey response was considerably greater than the 1974 survey; however the unit-year sample size was slightly less.

Table 4—Switchgear bus, indoor and outdoor 1979 survey data

Industry	Equipment subclass	Failure rate (failures per unit-year)	Median hours down time per failure
All	All	0.001 050	28
All	Insulated, above 600 V	0.001 129	28
All	Bare, all voltages	0.000 977	28
All	Bare, 0 V to 600 V	0.000 802	27
All	Bare, above 600 V	0.001 917	36
Petroleum/chemical	Insulated, above 600 V	0.002 020	40
Petroleum/chemical	Bare, all voltages	0.002 570	28
Petroleum/chemical	Bare, 0 V to 600 V	0.002 761	22
Petroleum/chemical	Bare, above 600 V	[a]	48

[a] Small sample size; fewer than eight failures.

The 1974 survey generated some controversy concerning bare and insulated buses; insulated bus equipment showed a significantly higher failure rate than bare bus above 600 V. An analysis of the 1974 database revealed that the majority of the data collected came from the petroleum/chemical industry. In the 1979

survey, the petroleum/chemical industry data was separated from the remaining industrial database. The resulting bare bus failure rate was significantly higher and the insulated bus failure rate lower in the 1979 survey than in the 1974 survey.

A comparison of the median downtime per failure in both surveys revealed no significant differences. It is important to emphasize that the duration of an outage is dependent on many factors, and without supplementary information on the operating procedures, maintenance type, spare parts inventory, etc., the data in these surveys should be viewed as general information.

Some important additional observations based on the 1979 survey are as follows:

a) Newer bus appears to experience a higher failure rate than older bus. This may be partly explained by improper installation, type of construction of new switchgear, etc., but is not completely consistent with the observation that failure rates are highly dependent on maintenance.

b) Outdoor bus shows a higher failure rate than indoor bus.

c) Primary and contributing causes of failures were investigated. Inadequate maintenance was one of the leading "suspected primary causes of failure" and exposure to contaminants (including dust, moisture, and chemicals) was the leading "contributing cause to failure." This tends to support the data showing outdoor bus with a relatively high failure rate.

d) The survey results on type of failures show a surprisingly high percentage of line-to-line failures, rather than line-to-ground.

5.5 1980 generator survey data

5.5.1 Introduction

The results of the 1980 generator survey data (see IEEE Committee Report [B12]) are summarized in Table 5. A *unit* in this survey was defined to include the generator's driver and its ancillary equipment, including the device from which the generator's output is made available to the "outside" world. The term *unit-year* was defined as the summation of the running times reported for each generator.

Table 5—Generator survey data, 1980

Equipment subclass	Average downtime per failure (h)	Failure rate
Continuous service steam turbine driven	32.7	0.16 900 failures per unit-year
Emergency and standby units reciprocating engines driven	478.0	0.00 536 failures per hour in use
Reciprocating engines driven	[a]	0.01 350 failures per start attempt

[a] Small sample size; fewer than eight failures.

Two major categories (i.e., continuously applied units and emergency or standby applied units) emerged from an evaluation of the responses. All of the continuous units were steam turbine driven, and all of the emergency or standby units were reciprocating engine driven. An important point to note on the data for emergency and standby units: Failure to start for automatically started units was counted as a failure, whereas failure to start for manually started units was not counted as a failure.

5.5.2 Reliability/availability guarantees of gas turbine and combined cycle generating units

Many industrial firms are now purchasing gas turbine generating units or combined cycle units that include both a gas turbine and a steam turbine. In some cases, the specification contains a reliability/availability guarantee. *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 221 (see Ekstrom [B7]) contains one manufacturer's suggestion on how to write a reliability/availability guarantee when purchasing such units; this is a very thorough description of the factors that need to be considered along with the necessary definitions. *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 221 also contains some 1993 data on the reliability/availability of gas turbine units that was collected by an independent data collection organization.

5.6 1979 survey of the reliability of transformers

5.6.1 Introduction

A survey published in 1973-1974 raised some interesting questions and created some controversy (see IEEE Committee Report [B10]). The most controversial items in this survey concerned the average outage duration time after a transformer failure in relation to the failure restoration method, and the comparatively high failure rate for rectifier transformers.

The 1979 survey form (see IEEE Committee Report [B11]) was improved considerably, taking lessons learned from the 1973-1974 version. Items felt to be of little significance in the past were omitted and the form was simplified to maximize the response. Data relating specifically to transformer reliability, such as rating, voltage, age, and maintenance were included in the new form. The most significant categories in the failed unit data are the causes of failure, the restoration method, restoration urgency, the duration of failure, and the transformer age at time of failure. The survey form of the 1979 survey (published in 1983) is shown in the *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, on page 114.

5.6.2 Failure rate and restoration method for power and rectified transformers survey results

The survey response for power transformers is summarized in Table 6 and the survey response for rectifier transformers is summarized in Table 7.

Table 6—Power transformers (1979 survey)

Equipment subclass	Failure rate (failures per unit-year)	Average repair time (hours per failure)	Average replacement time (hours per failure)
All liquid filled	0.0062	356.1	85.1
Liquid filled 300 kVA to 10 000 kVA	0.0059	297.4	79.3
Liquid filled > 10 000 kVA	0.0153	1178.5[a]	192.0[a]
Dry 300 kVA to 10 000 kVA	[a]	[a]	[a]

[a] Small sample size; fewer than eight failures.

Table 7—Rectifier transformers (1979 survey)

Equipment subclass	Failure rate (failures per unit-year)	Average repair time (hours per failure)	Average replacement time (hours per failure)
All liquid filled	0.0190	2316.0	41.4
Liquid filled 300 kVA to 10 000 kVA	0.0153	1644.0[a]	38.7[a]
Liquid filled > 10 000 kVA	[a]	[a]	[a]

[a] Small sample size; fewer than eight failures.

The survey results for the liquid-filled power transformers compared favorably between the 1973-1974 and 1979 surveys: 0.0041 and 0.0062 failures per unit-year, respectively. The 1979 survey also confirmed the fact that the failure rate for rectifier transformers (i.e., 0.0190) is much higher than those for the other transformer categories (i.e., 0.0062). This may be due to the severe duties to which they were subjected and/or the harsh environments in which they are housed.

Table 6 and Table 7 include data on restoration time versus restoration method. The data clearly indicate that the restoration of a unit to service by repair rather than replacement results in a much longer outage duration in every case. This is consistent with previous survey results. Despite this fact, in most categories a larger number of units were restored to service by repair. These results show the obvious benefits in having spares at the site or readily available. The data also provides some of the information necessary in the preparation of an economic justification for spares. The averages shown represent only those cases where restoration work was begun immediately. Those instances in which the repair or replacement was deferred were excluded to avoid distorting the average restoration time data.

5.6.3 Failure rate versus age of power transformers

The survey response for power transformer failures as a function of their age is summarized in Table 8.

Table 8—Failure rate versus age of power transformers (1979 survey)

Equipment subclass	Age[a] (years)	Number of units	Sample size (unit-years)	Number of failures[b]	Failure rate (failures per unit-year)
Liquid filled 300 kVA to 10 000 kVA	1 to 10	638	2625.5	19	0.0072
Liquid filled 300 kVA to 10 000 kVA	11 to 25	715	8846.5	47	0.0053
Liquid filled 300 kVA to 10 000 kVA	> 25	397	5938.0	36	0.0060
Liquid filled > 10 000 kVA	1 to 10	27	144.0	0[c]	—
Liquid filled > 10 000 kVA	11 to 25	28	283.5	7[c]	0.0246[c]
Liquid filled > 10 000 kVA	> 25	9	158.0	2[c]	0.0126[c]

[a] Age was the age of the transformer at the end of the reporting period.
[b] Relay or tap changer faults were not considered in calculation of failure rates or repair and replacement times.
[c] Small sample size; fewer than eight failures.

An examination of Table 8 reveals that the failure rates for power transformers was approximately equal in all three age groups. It can be seen that slightly higher failure rates for transformer units aged 1 year to 10 years and for units greater than 25 years may be attributable to “infant mortality” and to units approaching the end of their life, respectively.

5.6.4 Failure-initiating cause

Table 9 summarizes the failure-initiating cause data for power and rectifier transformers. This table reveals that a large percentage of transformer failures were initiated by some type of insulation breakdown or transient over-voltages.

Table 9—Failure-initiating cause for power and rectifier transformers (1979 survey)

	All power transformers		All rectifier transformers	
Failure-initiating cause	**Number of failures[a]**	**Percentage**	**Number of failures**	**Percentage**
Transient overvoltage disturbance (switching surges, arcing ground fault, etc.)	18	16.4%	2	13.3%
Overheating	3	2.7%	1	6.7%
Winding insulation breakdown	32	29.1%	2	13.3%
Insulation bushing breakdown	15	13.6%	1	6.7%
Other insulation breakdown	6	5.5%	3	20.0%
Mechanical breaking, cracking, loosening, abrading, or deforming of static or structural parts	8	7.3%	3	20.0%
Mechanical burnout, friction, or seizing of moving parts	3	2.7%	2	13.3%
Mechanically caused damage from foreign source (digging, vehicular accident, etc.)	3	2.7%	0	0.0%
Shorting by tools or other metal objects	1	0.9%	0	0.0%
Shorting by birds, snakes, rodents, etc.	3	2.7%	0	0.0%
Malfunction of protective relay control device or auxiliary device	5	4.6%	0	0.0%
Improper operating procedure	4	3.6%	0	0.0%
Loose connection or termination	8	7.3%	1	6.7%
Other	1	0.9%	0	0.0%
Continuous overvoltage	0	0.0%	0	0.0%
Low voltage	0	0.0%	0	0.0%
Low frequency	0	0.0%	0	0.0%
Total	110	100.0%	15	100.0%

[a] The initiating cause was not specified for two failures.

5.6.5 Failure-contributing cause

Table 10 summarizes the failure-contributing cause for power and rectifier transformers. Normal deterioration from age and cooling medium deficiencies were reported to have contributed to a large number of both power and rectifier transformer failures.

Table 10 —Failure-contributing cause for power and rectifier transformers (1979 survey)

	All power transformers		All rectifier transformers	
Failure-contributing cause	**Number of failures[a]**	**Percentage**	**Number of failures[b]**	**Percentage**
Persistent overloading	1	1.1%	0	0%
Abnormal temperature	5	5.5%	1	7.1%
Exposure to aggressive chemicals, solvents, dusts, moisture, or other contaminants	13	14.4%	1	7.1%
Normal deterioration from age	12	13.3%	4	28.60%
Severe wind, rain, snow, sleet, or other weather conditions	4	4.4%	0	0.0%
Lack of protective device	2	2.2%	0	0.0%
Malfunction of protective device	7	7.8%	0	0.0%
Loss, deficiency, contamination, or degradation of oil or other cooling medium	9	10.0%	3	21.50%
Improper operating procedure or testing error	3	3.3%	0	0.0%
Inadequate maintenance	7	7.8%	3	21.50%
Others	27	30.0%	1	7.1%
Exposure to nonelectrical fire or burning	0	0.0%	0	0.0%
Obstruction of ventilation by foreign object or material	0	0.0%	0	0.0%
Improper setting of protective device	0	0.0%	0	0.0%
Inadequate protective device	0	0.0%	1	7.1%
Total	90	100.0%	140	100.0%

[a] Failure-contributing cause not specified for 22 failures.
[b] Failure-contributing cause not specified for two failures.

5.6.6 Suspected failure responsibility

Table 11 summarizes the suspected failure responsibility for power and rectifier transformer failures. The respondents believed that manufacturer defects and inadequate maintenance were responsible for the majority of power transformer failures (i.e., 59.3%). Table 11 shows that inadequate operating procedures were a more significant cause of rectifier transformer failures (i.e., 31.2%) than inadequate maintenance.

Table 11—Suspected failure responsibility for power and rectifier transformers (1979 survey)

Failure-initiating cause	All power transformers		All rectifier transformers	
	Number of failures[a]	Percentage	Number of failures	Percentage
Manufacturer defective component or improper assembly	32	33.3	5	31.2
Transportation to site, improper handling	1	1.0	0	0.0
Application engineering, improper application	3	3.1	2	12.5
Inadequate installation and testing prior to start-up	6	6.3	0	0.0
Inadequate maintenance	25	26.0	2	12.5
Inadequate operating procedures	4	4.2	5	31.3
Outside agency—Personnel	3	3.1	0	0.0
Outside agency—Others	6	6.3	0	0.0
Others	16	16.7	2	12.5
Total	96	100.00	160	100.00

[a] Suspected failure responsibility not specified for 16 failures.

5.6.7 Maintenance cycle and extent of maintenance

The 1973-1974 survey asked the respondent to give an opinion of the maintenance quality as excellent, fair, poor, or none. It is very difficult to be completely objective in responding to this type of question. The 1979 survey, therefore, asked for a brief description of the extent of maintenance performed, the idea being to enable the reader to judge the benefits derived from a particular maintenance procedure. The large percentage of failures that resulted from inadequate maintenance shows the importance of a comprehensive preventive maintenance program and compilation of accurate data on the extent and frequency of the maintenance performed. Unfortunately, the response did not lend itself to reporting in tabular form. Maintenance information continues to be the most difficult to obtain and report for all equipment categories.

5.6.8 Type of failure

The 1979 survey limited the choices of failure type to “winding” and “other” as shown in Table 12 for power and rectifier transformers. Clearly, the most significant failure type was that occurring in power transformer windings.

Table 12—Type of failure for power and rectifier transformers (1979 survey)

Failure-initiating cause	All power transformers		All rectifier transformers	
	Number of failures	Percentage	Number of failures	Percentage
Winding	59	53	8	50
Other	53	47	8	50

5.6.9 Failure characteristics

The failure characteristics of power and rectifier transformers are shown in Table 13. As would be expected, the survey results show that about 75% of transformer failures resulted in their removal from service by automatic protective devices; however, the percentage requiring manual removal was

significant. Increasing use of transformer oil or gas analysis could be a factor here, enabling detection of incipient faults in their early stages, and thus permitting manual removal before a major failure occurs.

Table 13—Failure characteristic for power and rectifier transformers (1979 survey)

	All power transformers		All rectifier transformers	
Failure-initiating cause	**Number of failures**	**Percentage**	**Number of failures**	**Percentage**
Automatic removal by protective device	83	75	11	69
Partial failure, reducing capacity	5	5	0	0
Manual removal	23	20	5	31

5.6.10 Voltage rating

The failure rates for liquid-filled power transformers and rectifier transformers classified by their voltage ratings are shown in Table 14 and Table 15, respectively. An examination of Table 14 reveals the failure rate for the 600 V to 15 000 V transformers (i.e., 0.0052 failures per unit year) is fewer than that for the higher voltage units. The lack of data (i.e., small sample sizes) reported for rectifier transformers makes it impossible to draw any definite conclusions as to the effect of voltage or size on their failure rates.

Table 14—Failure rate versus voltage rating and size for power transformers (1979 survey)

Equipment subclass	Voltage (kV)	Number of units	Sample size (unit-years)	Number of failures	Failure rate (failures per unit-year)
Liquid filled 300 kVA to 10 000 kVA	0.16 to 15	1626	15 775	82	0.0052
Liquid filled 300 kVA to 10 000 kVA	> 15	124	1637	18	0.0110
Liquid filled > 10 000 kVA	> 15	52	490	9	0.0184

Table 15—Failure rate versus voltage rating for rectifier transformers (1979 survey)

Equipment subclass	Voltage (kV)	Number of units	Sample size (unit-years)	Number of failures	Failure rate (failures per unit-year)
All liquid filled	0.16 to 15	65	745	15	0.0201

5.7 1983 IEEE survey on the reliability of large motors

5.7.1 Introduction

A decision was made by the IEEE Motor Reliability Working Group to focus on motors that were of a critical nature in industrial and commercial installations, and thus, only motors larger than 200 hp (149 kW) were selected to be included in the survey (see IEEE Committee Report [B12] and *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 151). Another decision was made to limit the survey to only include motors that were 15 years old or less to focus on motors that were similar to those presently being manufactured and used today.

Failure rates are given for induction, synchronous, wound-rotor, and direct-current motors. Pertinent factors that affect the failure rates of these motors are identified. Data is presented on key variables, such as downtime per failure, failed component, causes of failure, and the time of failure discovery. The results of this recent survey are compared with four other surveys on the reliability of motors (see Albrecht, et al. [B3], Aquillino [B4], IEEE Committee Report [B13], IEEE Std 841-2001 [B19]). Details of the report are shown in *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 124. The results of the survey are summarized in 6.5. The term *large motor* is defined in 6.5 to be any motor whose horsepower rating exceeds 200 hp (149 kW).

5.7.2 Overall summary of failure rate for large motors

The 1983 survey included data reported for 360 failures on 1141 motors with a total service of 5085 unit-years. The overall summary of the survey results for induction, synchronous, wound rotor, and direct-current motors is shown in Table 16. Calendar time was used in the calculation of the unit-years of service (rather than the running time) to simplify the data collection procedure.

Table 16—Overall summary for large motors above 200 hp (149 kW)[a]

Number of plants in sample size	Sample size (unit-years)	Number of failures reported	Equipment subclass	Failure rate (failures per unit-year)	Average hours down-time per failure	Median hours down-time per failure
75	5085.0	360	All	0.0708	69.3	16.0
Induction						
33	1080.3	89	0 V to 1000 V	0.0824	42.5	15.0
52	2844.4	203	1001 V to 5000 V	0.0714	75.1	12.0
5	78.1	2[b]	5001 V to 15 000 V	[b]	[b]	[b]
Synchronous						
19	459.3	35	1001 V to 5000 V	0.0762	78.9	16.0
2	29.5	3[b]	5001 V to 15 000 V	[b]	[b]	[b]
Wound-rotor						
5	137.0	10	0 V to 1000 V	0.0730	[b]	[b]
9	251.1	8	1001 V to 5000 V	0.0319	[b]	[b]
2	39.0	4[b]	5001 V to 15 000 V	[b]	[b]	[b]
Direct current						
5	122.7	6[b]	0 V to 1000 V	[b]	[b]	[b]
1	30.0	—	1001 V to 5000 V	—	—	—

[a] See O'Donnell [B28].
[b] Small sample size; fewer than eight failures.

To summarize the important conclusions derived from the 1983 survey on the failure rates of large motors:

a) Induction and synchronous motors had approximately the same failure rate of 0.07 to 0.08 failures per unit-year.

b) Induction motors rated 0 V to 1000 V and those rated 1001 V to 5000 V had approximately the same failure rates.

c) Wound-rotor motors rated 0 V to 1000 V had a failure rate that was about the same as induction motors of the same rating.

d) Motors with intermittent duty operation had a failure rate that was about half as great as those with continuous duty.

e) Motors with fewer than one start per day had approximately the same failure rate as those motors with between one to 10 starts per day, which would indicate that up to 10 starts per day does not have a major effect on the motor failure rates.

5.7.3 Downtime per failure versus repair/replacement and urgency for repair for large motors

The comparison of the downtime per motor failure data for “repair” versus “replace with spare” is considered important when deciding whether a spare motor should be purchased when designing a new plant. The downtime per failure survey characteristics for all types of motors grouped together as a category is shown in Table 17.

Table 17 —Downtime per failure versus repair or replace with spare and urgency for repair—all types of motors above 200 hp (149 kW)[a]

	Number of failures	Average hours (downtime per failure)	Median hours (downtime per failure)
Repair—normal working hours[b]	87	97.7	24.0
Repair—round the clock	45	81.4	72.0
Replace with spare[c]	111	18.2	8.0
Low priority	4[d]	370.0[d]	400.0[d]
Not specified	6[d]	288.0[d]	240.0[d]
Total	251	69.3	14.0

[a] See O’Donnell [B28].
[b] 6570 h for one failure omitted.
[c] 960 h for one failure omitted.
[d] Small sample size; fewer than eight failures.

An examination of Table 17 shows the effect on the repair time that the urgency for repair has had. There were 45 cases of motor failures where the repair activities were carried out on a round-the-clock basis. There were four cases of motor failures where low-priority urgency resulted in a very long downtime; it is important to exclude these cases when making decisions on the design of industrial and/or commercial power systems. In general, the average downtime per failure is about five times larger for repair versus replace with spare.

5.7.4 Failed component—large motors

The identified motor component that failed is shown in Table 18 for induction, synchronous, wound-rotor, and direct-current motors.

Table 18 —Failed component—Large motors (above 200 hp [149 kW]) (number of failures)

Failed component[a]	Induction motors	Synchronous motors	Wound rotor motors	Direct-current motors	Total (all types)
Bearings	152	2	10	2	166
Windings	75	16	6		97
Rotor	8	1	4		13
Shaft or coupling	19				19
Brushes or slip ring	—	6	8	2	16
External devices	10	7	1		18
Not specified	40	9		2	51
Total	304	41	29	6	380

[a] Some respondents reported more than one failed component per motor failure.

It can be seen that the two largest categories reported are motor bearing and winding failures with 166 and 97 failures, respectively, out of a total of 380 failures. Bearings and windings represent 44% and 26%, respectively, of the total number of motor failures.

5.7.5 Failed component versus time of discovery—large motors

Data on the failed component versus the time the failure was discovered is shown in Table 19. It can be seen that 60.5% of the failures found during maintenance or test are bearings. Many users consider that it is very important to find as many failures as possible during maintenance or test rather than normal operation. Bearings and windings represent 36.6% and 33.1%, respectively, of the failures discovered during normal operation.

Table 19 —Failed component versus time of discovery (all types of motors above 200 hp [149 kW]) (percentage of failures)

	Time of discovery		
Failed component	**Normal operation**	**Maintenance or test**	**Other**
Bearing	36.6	60.5	50.0
Windings	33.1	8.3	28.6
Rotor	5.1	1.8	0.0
Shaft or coupling	5.8	8.3	14.3
Brushes or slip rings	3.1	7.3	0.0
External devices	5.0	3.7	0.0
Not specified	11.3	10.1	7.1
Total percentage of failures	100.0	100.0	100.0
Total number of failures	257	109.0	14.0

5.7.6 Causes of large motor bearing and winding failures

The causes of motor failures categorized according to the failure initiator, the failure contributor, and the failure's underlying cause are shown in Table 20 for induction, synchronous, and all motors.

Table 20 —Causes of failure versus motor type and versus bearing and winding failures—motors above 200 hp (149 kW) (percentage of failures)

All motor types—failed component		All types of motors %	Induction motors %	Synchronous motors %	Causes of failures
Bearings %	Windings %				
					Failure initiator
0.0	4.1	1.5	1.4	0.0	Transient overvoltage
12.4	21.4	13.2	14.7	0.0	Overheating
1.9	36.7	12.3	11.9	21.1	Other insulation breakdown
50.3	10.2	33.1	37.4	5.2	Mechanical breakage
3.7	11.2	7.6	5.8	23.7	Electrical fault or malfunction
0.0	2.1	0.9	0.7	2.6	Stalled motor
31.7	14.3	31.4	28.1	47.4	Other
100.0	100.0	100.0	100.0	100.0	Total percentage of failures
161.0	98.0	341.0	278.0	38.0	Total number of failures
					Failure contributor
1.4	6.5	4.2	4.9	2.7	Persistent overheating
0.7	7.6	3.0	3.4	0.0	High ambient temperature
2.7	18.5	5.8	6.7	2.7	Abnormal moisture
0.0	5.4	1.5	1.5	2.7	Abnormal voltage
0.0	1.1	0.6	0.7	0.0	Abnormal frequency
21.8	8.7	15.5	17.6	5.4	High vibration
5.4	6.5	4.2	4.5	2.7	Aggressive chemicals
31.3	5.4	15.2	16.9	8.1	Poor lubrication
0.0	7.6	3.9	2.2	2.7	Poor ventilation or cooling
20.4	18.5	26.4	24.0	51.4	Normal deterioration from age
16.3	14.2	19.7	17.6	21.6	Other
100.0	100.0	100.0	100.0	100.0	Total percentage of failures
147.0	92.0	330.0	267.0	37.0	Total number of failures
					Failure underlying cause
17.8	10.9	20.1	20.3	22.2	Defective component
14.5	10.9	12.9	15.9	0.0	Poor installation/testing
27.6	19.6	21.4	22.8	11.1	Inadequate maintenance
2.0	6.5	3.6	3.3	2.8	Improper operation
0.7	0.0	0.6	0.8	0.0	Improper handling/shipping
7.9	7.6	6.1	6.5	2.8	Inadequate physical protection
2.6	15.2	5.8	5.3	11.1	Inadequate electrical protection
7.2	5.4	6.8	5.7	5.6	Personnel error
2.0	3.3	3.9	2.8	13.9	Outside agency—not personnel
5.9	4.3	4.9	4.9	0.0	Motor-driven equipment mismatch
11.8	16.3	13.9	11.7	30.5	Other
100.0	100.0	100.0	100.0	100.0	Total percentage of failures
152.0	92.0	309.0	246.0	36.0	Total number of failures

Mechanical breakage is the largest failure initiator for induction motors. Normal deterioration from age, high vibration, and poor lubrication are the major failure contributors to induction motor failures. Inadequate maintenance and defective component are the largest underlying causes of induction motor failures.

Electrical fault or malfunction and other insulation breakdown are the major failure initiators for synchronous motors. Normal deterioration from age is the major fault contributor of synchronous motors. Defective component is the largest underlying cause of synchronous motor failures.

Table 20 shows a correlation between bearing failures and the causes of failure: 50.3% of bearing failures were initiated by mechanical breakage; 31.3% and 21.8%, respectively, had poor lubrication and high vibration as failure contributors; and 27.6% blamed inadequate maintenance as the underlying cause.

Table 20 also shows a correlation between winding failures and the causes of failure: 36.7% of the winding failures had other insulation breakdown as the initiator; 18.5% and 18.5%, respectively, had normal deterioration from age and abnormal moisture as failure contributors; 19.6% had inadequate maintenance and 15.2% had inadequate electrical protection as the underlying cause.

It is of interest to note that inadequate maintenance was the largest underlying cause of both bearing and winding failures. A special study of the 71 failures attributed to inadequate maintenance is shown in Table 21. It can be clearly seen that 59.1% of the motor components that failed were bearings, 52.1% of the failures were initiated by mechanical breakage, and 43.7% of the failures had poor lubrication as a failure contributor.

Table 21 —Failures caused by inadequate maintenance versus failed component, failure initiator, and failure contributor (all types of motors above 200 hp [149 kW])[a]

Percentage	Failed component
59.1	Bearing
25.4	Winding
1.4	Rotor
0.0	Shaft or coupling
8.5	Brushes or slip rings
1.4	External device
4.2	Other
100.0	Total percentage (number of failures = 71)
	Failed initiator
0.0	Transient overvoltage
4.2	Overheating
14.1	Other insulation breakdown
52.1	Mechanical breakage
2.8	Electrical fault or malfunction
0.0	Stalled motor
26.8	Other
100.0	Total percentage (number of failures = 71)
	Failed contributor
0.0	Persistent overloading
4.2	High ambient temperature
7.0	Abnormal moisture
0.0	Abnormal voltage
0.0	Abnormal frequency
4.2	High vibration
9.9	Aggressive chemical
43.7	Poor lubrication
1.4	Poor ventilation/cooling
18.3	Normal deterioration from age
11.3	Other
100.0	Total percentage (number of failures = 71)

[a] See O’Donnell [B28].

5.7.7 Other significant results

5.7.7.1 Introduction

Several additional parameters were reported in O’Donnell [B28] in terms of their effect on the failure rate of motors above 200 hp (149 kW). These included the effect of horsepower, speed, enclosure, environment, duty cycle, service factor (S.F.), average number of starts per day, grounding practice, maintenance quality, maintenance cycle, type of maintenance performed, and months since last maintenance prior to the failure.

Some combinations of these parameters, two at a time, have also been studied and reported (see O'Donnell [B28]).

5.7.7.2 Open versus enclosed motors

The following significant conclusions were reached:

a) Open motors had a higher failure rate than weather-protected or enclosed motors.

b) Outdoor motors had a lower failure rate than indoor motors because most outdoor motors were weather protected or enclosed, and most indoor motors were open.

5.7.7.3 Service factor

The 1.15 S.F. induction motors had a higher reported failure rate than 1.0 S.F. induction motors, but the opposite was true for synchronous motors.

5.7.7.4 Speed and horsepower

The failure rate for induction motors did not vary significantly among the three speed categories (i.e., 0 RPM to 720 RPM, 721 RPM to 1800 RPM, and 1801 RPM to 3600 RPM). The highest failure rate was in the middle speed category, while the lowest failure rate was in the higher speed category. The 201 hp (150 kW) to 500 hp (373 kW) induction motors had approximately the same failure rate as 501 hp (374 kW) to 5000 hp (3730 kW) induction motors in each of the three speed ranges studied.

Synchronous motors in the speed category 0 RPM to 720 RPM had a higher failure rate than synchronous motors in the 721 RPM to 1800 RPM category. There were no respondents for the 1801 RPM to 3600 RPM category.

5.7.8 Data supports chemical industry motor standard

Reliability data for induction motors from both the 1983 IEEE survey and the 1973-1974 IEEE survey (see *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, pages 1 and 61) supported the need for several of the features incorporated into IEEE Std 841-2001 [B19]. The IEEE surveys show the need for improved reliability of bearings and windings and, in some cases, the need for better physical protection against aggressive chemicals and moisture. Some of the more significant recommendations for an IEEE Std 841-2001 [B19] motor include:

a) Totally enclosed fan-cooled (TEFC) enclosure

b) Maximum 80 °C rise at 1.0 S.F.

c) Contamination protection for bearings and grease reservoirs

d) Three-year continuous L-10 bearing life

e) Maximum bearing temperature of 45 °C rise (50 °C rise on two-pole motors)

f) Cast iron frame construction

g) Nonsparking fan

h) Single connection point per phase in terminal box

i) Maximum sound power level of 90 dBA

j) Corrosion-resistant paint, internal joints and surfaces, and hardware

IEEE Std 841-2001 [B19] was tailored for the petroleum/chemical industry; however, it can be beneficial for other industries with similar requirements.

5.7.9 Comparison of 1983 motor survey with other motor surveys

5.7.9.1 Introduction

One of the primary purposes of comparing the results of 1983 motor survey with previous surveys and other surveys (see Albrecht, et al. [B2], [B3], and the "Summary of Replies to the 1982 Technical Questionnaire" [B40]) is to attempt to identify trends in the failure characteristics of motors (i.e., changing failure rates with time, varying causes of motor failures, assessing the impact of maintenance practices).

5.7.9.2 1983 EPRI and 1983-1985 IEEE surveys

The size and scope of the IEEE Working Group and EPRI motor surveys is shown in Table 22. The motor failure rate of 0.035 failures per unit-year in the EPRI-sponsored study of the electric utility industry is about half the IEEE failure rate of 0.0708 failures per year.

Table 22 —Size and scope comparison of IEEE1983-1985 motor survey and EPRI-sponsored motor survey in electric utility power plants[a]

Parameter	IEEE Working Group	EPRI Phase I
Horsepower (kilowatts)	> 200 (149 kW)	100 (75 kW) and up
Number of companies/utilities	33	56
Number of plants or units	75	132
Number of motors	114 100	47 970
Total population (unit-years)	508 500	24 914 100
Total failures	3600	871 100
Failure rate (all motors)	0.07 080	0.03 500[b]

[a] See O'Donnell [B28].
[b] To first failure.

The percentage of motor failures classified by component in the two surveys is shown in Table 23. Similar results were obtained in these two studies on the failed component, with bearing, winding, and rotor-related percentages that were each about the same.

Table 23 —Failure by component comparison of the IEEE 1983-1985 motor survey and EPRI-sponsored survey

IEEE Working Group	EPRI Phase I
44% bearings	41% bearing related
26% windings	37% stator related
8% rotor/shafts/couplings	10% rotor related

Table 24 shows some differences between the two studies on the causes of failures. The IEEE survey found inadequate maintenance, poor installation/testing, and misapplication to be a significantly larger percentage of the causes of motor failures, while the EPRI study attributed a larger percentage to the manufacturer. In addition, the EPRI study had a much larger percentage of failures attributed to other, or not specified, causes. Additional results from the EPRI-sponsored study were given in a later paper (see Albrecht, et al. [B3]).

Table 24 —Cause of failure comparison—IEEE 1983-1985 motor survey and EPRI-sponsored motor survey

Failure cause	EPRI Phase I		IEEE Working Group		Failure cause
	Number	Percent	Number	Percent	
Manufacturer design workmanship	401	32.8	62	17.2	Defective component
Misoperation	124	10.2	32	8.9	Improper operation/personnel error
Misapplication	83	6.8	52	14.5	Misapplication, motor-driven equipment mismatch, inadequate electrical protection, inadequate physical protection
			66	18.3	Inadequate maintenance
			40	11.1	Poor installation/testing
			12	3.3	Outside agency other than personnel
			2	0.6	Improper handling/shipping
Other or not specified	613	50.2	94	26.1	Other or not specified
Total failures	1221	100.0	360	100.0	Total failures

5.7.9.3 1982 Doble data and 1983-1985 IEEE surveys

A 1982 Doble survey (see "Summary of Replies to the Technical Questionnaire" [B40]) in the electric utility industry (for motors 1000 hp [746 kW] and up and not over 15 years of age) reported 68 insulation-related failures in 2078 unit-years of service during the year 1981. This gives an insulation-related failure rate of 0.033 failures per unit-year. This can be compared with a winding failure rate of 26% times 0.0708, which equals 0.018 failures per unit-year that can be calculated from the 1983-1985 IEEE survey of motors above 200 hp (149 kW) and not older than 15 years, shown in Table 22 and Table 23.

5.7.9.4 IEEE surveys 1973-1974 and 1983-1985

Table 25 shows the results from the 1973-1974 IEEE motor reliability survey of industrial plants (see IEEE Committee Report [B13]). This survey covered motors 50 hp (37.3 kW) and larger, and had no limit on the age of the motor. Those results can be compared to Table 16 for the 1983-1985 IEEE survey of motors above 200 hp (149 kW) and not older than 15 years. The 1983-1985 failure rates of induction motors and synchronous motors were about double those from the 1973-1974 survey for motors 601 V to 15 000 V.

Table 25—1973-1974 IEEE overall summary for motors 50 hp (37.3 kW) and larger

Number of plants in sample size	Sample size (unit-years)	Number of failures reported	Equipment subclass	Failure rate (failures per unit-year)	Average hours down-time per failure	Median hours down-time per failure
—	42 463	561	All	0.0132	111.6	—
17	19 610	213	Induction, 0 V to 600 V	0.0109	114.0	18.3
17	4229	172	Induction, 5001 V to 15 000 V	0.0404	76.0	153.0
2	13 790	10	Synchronous, 1001 V to 5000 V	0.0007	35.3	35.3
11	4276	136	Synchronous, 5001 V to 15 000 V	0.0318	175.0	153.0
6	558	310	Direct current	0.0556	37.5	16.2

5.7.9.5 AIEE 1962 and 1983-1985 IEEE surveys

Table 26 shows the results from the 1962 AIEE motor reliability survey of industrial plants. This survey covered motors 250 hp (187 kW) and larger and had no limit on the age of the motor. The failure rates for both induction motors and synchronous motors from the 1962 AIEE survey are within 30% of those shown in Table 16 for the 1983-1985 IEEE survey of motors above 200 hp (149 kW) and not older than 15 years. The two surveys conducted 21 years apart show remarkably similar results.

Table 26—AIEE overall summary for motors 250 hp (187 kW) and larger, United States and Canada, 1962

Number of plants in sample size	Sample size (unit-years)	Number of failures reported	Equipment subclass	Failure rate (failures per unit-year)	Average hours down-time per failure	Median hours down-time per failure
46	1420	140	Induction	0.0986	78.0	70.0
53	600	31	Synchronous	0.0650	149.0	68.0

5.7.9.6 1994 IEEE PES survey of overhead transmission lines

The IEEE Power Engineering Society conducted an extensive survey of the outages of overhead transmission lines 230 kV and above in the United States and Canada (see Adler, et al. [B1]). This is included as *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 258 and covers 230 kV, 345 kV, 500 kV, and 765 kV and includes both permanent and momentary outages. Line-caused outages have been separated from terminal-caused outages. Data are given on the type of fault that caused the outage. Faults can result in voltage sags at the entrance to industrial and commercial installations.

6. Part 3: Equipment reliability surveys conducted prior to 1976

6.1 Introduction

From 1973 to 1975, the Power Systems Reliability Subcommittee of the IEEE Industrial Power Systems Department conducted and published surveys of electrical equipment reliability in industrial plants (see IEEE Committee Reports [B11], [B13]) including circuit breakers, motor starters, disconnect switches, bus duct, open wire, cable, cable joints, and cable terminations. Those reliability surveys of electrical equipment and electric utility power supplies were extensive, collecting data such as:

a) Failure rate

b) Failure duration

c) Failure modes

d) Causes of failure

e) Failure repair method and failure repair urgency

f) Loss of motor load versus time of power outage

The section also discusses the maximum length of time of an interruption of electrical service that will not stop plant production, plant restart time after service is restored following a failure that caused a complete plant shutdown, and the cost of power interruptions to industrial plants and commercial buildings. In addition, the data show multiple utility interdependence and equipment failure versus quality of maintenance.

The preceding data was taken from the IEEE surveys of industrial plants (see Albrecht, et al. [B3] and the "Report of Equipment Availability for a 10 Year Period" [B33]) and commercial buildings (see O'Donnell [B28]). The detailed reports are given in *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, pages 1, 61, 87, and 95. A later survey (IEEE Committee Report [B13]) of the reliability of switchgear bus is included in *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*. More recent surveys on transformers, large motors, cable, terminations, and splices are included in *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, pages 114, 124, and 151, respectively. Recent surveys on circuit breakers are shown in *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, pages 161 and 170. A 1989 survey on diesel and gas turbine generating units is included in *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 187.

Clause 7 presents data for specific types of equipment according to Table 27.

Table 27 —Part 3 equipment reliability table reference guide

Electrical equipment type		Surveys prior to 1976
Motors	> 50 hp (37.3 kW)	Table 35
	> 200 hp (149 kW)	Table 35
	> 250 hp (187 kW)	Table 35
Motor starters		Table 30, Table 31, Table 32, Table 33, Table 35, Table 36
Generators		0
Transformers	Power	Table 35, Table 36
	Rectifier	Table 35, Table 36
Circuit breakers		Table 28, Table 29, Table 31, Table 32, Table 33 Table 35, Table 36
Disconnect switches		Table 30, Table 31, Table 32, Table 33, Table 35, Table 36
Bus duct		Table 30, Table 31, Table 32, Table 33, Table 35
Switch gear	Bus insulated	Table 35
	Bus bare	Table 35
Open wire		Table 30, Table 31, Table 32, Table 33, Table 35, Table 36
Cable		Table 30, Table 31, Table 32, Table 33, Table 35, Table 36
Cable joints		Table 30, Table 31, Table 32, Table 33, Table 35, Table 36
Cable terminations		Table 30, Table 31, Table 32, Table 33, Table 35, Table 36
Electric utility power supplies		Table 34, Table 35

6.2 Reliability of electrical equipment (1974 survey)

6.2.1 Introduction

In compiling the data for the 1974 survey, a failure was defined as any trouble with a power system component that causes any of the following effects:

a) Partial or complete plant shutdown or below-standard plant operation

b) Unacceptable performance of user’s equipment

c) Operation of the electrical protective relaying or emergency operation of the plant electric system

d) De-energization of any electric circuit or equipment

A failure on a public utility supply system may cause the user to have either of the following:

— A power interruption or loss of service

— A deviation from normal voltage or frequency outside the normal utility profile

All of the electrical equipment categories listed in this section have eight or more failures. This is considered an adequate sample size (see Patton [B32]) in order to have a reasonable chance of determining a failure rate within a factor of 2. Failure rate and average downtime per failure data for an additional six categories of equipment are contained in IEEE Committee Report [B13] (*Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 1).

6.2.2 Failure modes of circuit breakers

6.2.2.1 Introduction

The failure modes of metal-clad drawout and fixed-type circuit breakers are shown in Table 28. Of primary concern to industrial plants is the large percentage of circuit breaker failures (i.e., 42%) that opened when they should not. This type of circuit breaker failure can significantly affect plant processes and may result in a total plant shutdown. Also, a large percentage (32%) of the circuit breakers failed while in service (not while opening or closing). *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, pages 161 and 170, and the "Report on Power Circuit Troubles—1975" [B39] contain additional circuit breaker reliability information.

Table 28 —Failure modes of circuit breakers[a] (1974 survey)

All circuit breakers %	Metal-clad drawout			Fixed-type[b]		Failure characteristics
	All %	0 V to 600 V 601 V to 15 000 V %	All sizes %	0 V to 600 V, all sizes %	All %	
5	5	2	7	8	6	Failed to close when it should
9	12	21	0	0	2	Failed while opening
42	58	49	71	5	4	Opened when it should not
7	6	4	9	5	4	Damaged while successfully opening
2	1	0	0	0	4	Damaged while closing
32	16	24	10	77	32	Failed while in service (not while opening or closing)
1	0	0	0	0	2	Failed during testing or maintenance
1	2	0	3	0	0	Damage discovered during testing or maintenance
1	0	0	0	5	5	Other
100	100	100	100	100	100	Total percentage
166	117	53	59	39	48	Number of failures in total percentage
8	7	0	7	1	1	Number not reported
173	124	53	66	40	49	Total failures

[a] *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 170 contains some limited data from a later IEEE survey. *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 161 contains data for circuit breakers above 63 kV from a CIGRE 13-06 worldwide survey with a very large population.
[b] Includes molded case.

6.2.2.2 Trip units on low-voltage breakers

Most modern low-voltage power circuit breakers are purchased with a solid-state trip unit rather than an electromechanical trip unit. Many older low-voltage breakers have been retrofitted with a solid-state trip

that replaced an electromechanical trip unit. A comparison has been made of the reliability of these two types of trip units based on a 1996 IEEE survey of low-voltage breaker operation as found during maintenance (see O'Donnell [B30]).

Electromechanical trip units had an unacceptable operation about twice as often as solid-state units. A summary of the most important results is given in Table 29. The complete results are included in *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 266.

Table 29 —Survey of low-voltage power breaker operation as found during maintenance tests—electromechanical versus solid-state trip type unit; new solid state units versus used (older) solid state units

	Trip unit type			
	Electromechanical		Solid-state	
	Number of failures	%	Number of failures	%
Unacceptable operation				
Trip unit failed to operate	81	7.7	28	3.0
Trip unit out of specification	60	5.7	24	2.6
Mechanical operations (springs, arms/levers, hardened lubricant)	26	2.5	19	2.0
Power contacts (alignment, incorrect pressure, pitted)	25	2.4	19	2.0
Arc chutes (clean, replace/repair, chipped)	6	0.6	6	0.7
Auxiliary contacts	4	0.4		
Total unacceptable	204	19.4%	100	10.7%
Acceptable operation	850	80.6%	835	89.3%
Total number of tests	1054	100.0%	935	100.0%

6.2.2.3 Failure characteristics of other electrical equipment

The failure characteristics of electrical equipment (excluding transformers and circuit breakers) are shown in Table 30. The dominant failure characteristic for this equipment is that it failed in service. A large percentage of the damage to motor starters (36%), disconnect switches (18%), and cable terminations (12%) was discovered during testing or maintenance.

Table 30 —Failure characteristics of other electrical equipment

Motor starters %	Disconnect switches %	Bus duct %	Open wire %	Cable %	Cable joint %	Cable terminations %	Failure characteristics
37	72	90	68	92	96	80	Failed in service
6	3	5	2	2	4	2	Failed during testing or maintenance
36	18	0	1	2	0	12	Damage discovered during testing or maintenance
20	6	5	6	3	0	6	Partial failure
2	1	0	23	1	0	0	Other

6.2.2.4 Causes and types of failures of electrical equipment

Table 31 shows the breakdown of the reported failures by damaged parts and failure type.

Table 31 —Failure, damaged part, and failure type (1974 survey)

Circuit breakers %	Motor starters %	Disconnect switches %	Bus duct %	Open wire %	Cable %	Cable joints %	Cable terminations %	Failure, damaged part
0	5	0	15	0	5	0	0	Insulation—winding
2	0	1	10	1	0	0	12	Insulation—bushing
19	10	14	65	6	83	91	74	Insulation—other
1	0	0	0	0	3	0	0	Mechanical—bearings
11	16	9	0	0	0	0	0	Mechanical—other moving parts
6	2	30	0	4	1	0	4	Mechanical—other
6	13	8	0	3	1	0	0	Other electric—auxiliary device
28	2	1	0	3	1	0	0	Other electric—protective device
1	0	0	0	0	0	0	0	Tap changer—no load type
0	0	0	0	0	0	0	0	Tap changer—load type
26	52	37	10	83	6	9	10	Other
								Failure type
33	14	15	70	34	73	70	55	Flashover or arcing involving ground
10	20	4	30	23	1	9	4	All other flashover or arcing
19	55	47	0	25	7	20	37	Other electric defects
11	11	14	0	6	5	0	4	Mechanical defect
27	0	20	0	12	14	0	0	Other

The data presented in Table 32 indicate that the respondents suspected inadequate maintenance and manufacturer-defective components were responsible for a significant percentage of the reported failures.

Table 32 —Suspected failure responsibility, failure-initiating cause, and failure-contributing cause

Circuit breakers %	Motor starters %	Disconnect switches %	Bus duct %	Open wire %	Cable %	Cable joints %	Cable terminations %	Suspected failure responsibility
23	18	29	26	0	16	0	0	Manufacturer-defective component
0	0	0	0	0	0	0	0	Transportation to site—defective handling
4	51	6	16	2	8	0	18	Application engineering—improper application
3	0	4	5	9	14	50	38	Inadequate installation and testing prior to startup
23	8	13	16	30	10	18	32	Inadequate maintenance
6	3	39	0	2	3	0	0	Inadequate operating procedures
5	0	1	5	5	4	5	0	Outside agency—personnel
1	0	0	0	211	6	2	8	Outside agency—other
35	20	8	32	31	39	25	14	Other
								Failure-initiating cause
4	0	8	6	0	0	0	0	Persistent overloading
1	0	3	0	0	0	2	0	Above-normal temperature
0	0	1	0	0	0	0	0	Below-normal temperature
2	0	0	0	28	14	13	10	Exposure to aggressive chemicals or solvents
0	0	0	17	1	8	22	12	Exposure to abnormal moisture or water
0	0	0	0	3	2	0	0	Exposure to nonelectrical fire or burning
0	0	0	0	0	1	0	0	Obstruction of ventilation by objects or material
17	40	5	49	3	30	29	24	Normal deterioration from age
1	0	0	11	30	16	2	16	Severe wind, rain, snow, sleet, or other weather conditions
2	0	0	0	1	0	0	0	Protective relay improperly set
1	2	0	0	0	0	0	0	Loss or deficiency

Circuit breakers %	Motor starters %	Disconnect switches %	Bus duct %	Open wire %	Cable %	Cable joints %	Cable terminations %	Suspected failure responsibility
23	18	29	26	0	16	0	0	Manufacturer-defective component
0	0	0	0	0	0	0	0	Transportation to site—defective handling
4	51	6	16	2	8	0	18	Application engineering—improper application
3	0	4	5	9	14	50	38	Inadequate installation and testing prior to startup
23	8	13	16	30	10	18	32	Inadequate maintenance
6	3	39	0	2	3	0	0	Inadequate operating procedures
5	0	1	5	5	4	5	0	Outside agency—personnel
1	0	0	0	211	6	2	8	Outside agency—other
35	20	8	32	31	39	25	14	Other
								of lubricant
0	0	0	0	0	0	0	0	Loss or deficiency of oil or cooling medium
10	3	0	6	2	3	0	8	Misoperation or testing error
3	1	26	0	2	1	0	0	Exposure to dust or other contaminants
56	54	54	11	30	24	32	30	Other

6.2.2.5 Failure repair method and failure repair urgency

The failure repair method and the failure repair urgency had a significant effect on the average downtime per failure. Table 33 shows the percent of the time that different repair methods and urgencies occurred. A special study on this subject is reported in Tables 50, 51, 55, and 56 of Patton [B32] (*Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 61) for circuit breakers and cables.

Table 33—Failure repair method and failure repair urgency (1974 survey)

Circuit breaker %	Motor starters %	Disconnect switches %	Bus duct %	Open wire %	Cable %	Cable joints %	Cable terminations %	Failure repair method
51	33	30	66	70	47	87	60	Repair of failed component in place or sent out for repair
49	67	70	35	9	53	13	34	Repair by replacement of failed component with spare
0	0	0	0	21	0	0	0	Other
								Failure repair urgency
73	66	20	80	55	66	56	53	Requiring round-the-clock all-out efforts
22	34	80	15	26	28	22	31	Requiring repair work only during regular workday, perhaps with overtime
5	0	0	5	0	6	22	16	Requiring repair work on a non-priority basis
0	0	0	0	19	0	0	0	Other

6.2.2.6 Reliability of electric utility power supplies to industrial plants

The failure rate and the average downtime per failure of electric utility supplies to industrial plants are given in Table 34. Additional details are given in *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, and page 95 of the paper "Report on Equipment Availability for 10 Year Period 1965-74" [B33]. A total of 87 plants participated in the IEEE survey covering the period from 1 January 1968 through October 1974.

Table 34 —IEEE survey of reliability of electric utility supplies to industrial plants (IEEE Committee report, 1975 survey)

	Failures per unit-year[a]			Average duration (minutes per failure)[a]		
	λΣ	λP	λ	*rS*	*rR*	*r*
Single-circuit utility supplies						
Voltage level						
V ≤ 15 kV	0.905	2.715	3.621	3.5	165	125
15 kV < V ≤ 35 kV		1.657	1.657		57	57
V > 35 kV	0.527	0.843	1.370		59	37
All	0.556	1.400	1.956	2.3	110	79
Multiple-circuit utility supplies (all voltage levels)						
Switching scheme						
All breakers closed	0.255	0.057	0.312	8.5	130	31
Manual throw-over	0.732	0.118[b]	0.850	8.1	84[b]	19
Automatic throw-over	1.025	0.171	1.196	0.6	96	14
All	0.453	0.085	0.538	5.2	110	22
Multiple-circuit utility supplies (all switching schemes)						
Voltage level						
V ≤ 15 kV	0.640	0.148	0.788	4.7	149	32
15 kV < V ≤ 35 kV	0.500	0.064[b]	0.564	4.0	115[b]	17
V > 35 kV	0.357	0.067	0.424	6.1	184	34
Multiple-circuit utility supplies (all circuit breakers closed)						
Voltage level						
V ≤ 15 kV	0.175	0.088[b]	0.263	0.7	335[b]	112
15 kV < V ≤ 35 kV	0.342	0.019[b]	0.361	7.0	120[b]	13
V > 35 kV	0.250	0.061	0.311	11.0	203	49

[a] Failure rates λS and λ*R* and average durations *rS* and *rR* are, respectively, rates and durations of failures terminated by switching and by repair or replacement. Unsubscripted rates and durations are overall values.
[b] Small sample size; fewer than eight failures.

The survey results shown in Table 34 have distinguished between power failures that were terminated by a switching operation and those requiring repair or replacement of equipment. The latter have a much longer outage duration time. Some of the conclusions that can be drawn from the IEEE data are:

a) The failure rate for single-circuit supplies is about 6 times that of multiple-circuit supplies that operate with all circuit breakers closed, and the average duration of each outage is about 2.5 times as long.

b) Failure rates for multiple-circuit supplies that operate with either a manual or an automatic throw-over scheme are comparable to those for single-circuit supplies, but throw-over schemes have a smaller average failure duration than single-circuit supplies.

c) Failure rates are highest for utility supply circuits operated at distribution voltages and lowest for circuits operated at transmission voltages (greater than 35 kV).

It is important to note that the data in Table 34 shows that the two power sources of a double-circuit utility supply are not completely independent. This is analyzed in an example, where (for the one case analyzed)

the actual failure rate of a double-circuit utility supply is more than 200 times larger than the calculated value for two completely independent utility power sources.

Utility supply failure rates vary widely in various locations. One of the significant factors in this difference is believed to be different exposures to lightning storms. Thus, average values for the utility supply failure rate may not be appropriate for use at any one location. Local values should be obtained, if possible, from the utility involved, and these values should be used in reliability and availability studies.

An earlier IEEE reliability survey of electric power supplies to industrial plants was published in 1973 and is reported in Table 3 of Albrecht, et al. [B3] (*Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 1). The earlier survey had a smaller database and is not believed to be as accurate as the one summarized in Table 35.

6.2.2.7 Method of electrical service restoration to plant

The 1973-1975 IEEE data on method of electrical service restoration to plant is shown in Table 35.

The most common methods of service restoration to a plant are replacement of a failed component with a spare or the repair of the failed component. The primary selection or secondary selection is used only 22% of the time. This would indicate that most power distribution systems in this IEEE survey were radial.

Table 35—Method of service restoration (1974 survey)

Total	Electric utilities power supplies	Trans-formers	Circuit breakers	Motor starters	Motors	Generators	Disconnect switches	Switch gear bus: Insulated	Switch gear bus: Bare	Bus duct	Open wire	Cable	Cable joints	Cable terminations	Method of service restoration
7%	1%	3%	6%	0%	5%	20%	0%	58%	25%	20%	13%	14%	28%	19%	Primary selective—manual
2%	8%	0%	1%	0%	0%	0%	0%	0%	5%	0%	4%	5%	8%	0%	Primary selective—automatic
11%	1%	25%	6%	0%	14%	33%	0%	17%	10%	10%	2%	20%	32%	23%	Secondary selective—manual
2%	1%	3%	8%	0%	0%	0%	0%	0%	0%	0%	1%	0%	8%	4%	Secondary selective—automatic
0+%	0%	0%	0%	0%	0%	0%	0%	0%	5%	0%	0%	0%	0%	0%	Network protector operation—automatic
22%	5%	25%	11%	12%	30%	20%	3%	17%	20%	35%	31%	42%	24%	27%	Repair of failed component
22%	2%	39%	38%	10%	29%	14%	77%	0%	10%	35%	6%	2%	0%	12%	Replacement of failed component
12%	81%	0%	1%	0%	0%	13%	0%	0%	0%	0%	1%	1%	0%	0%	Utility service restored
22%	1%	5%	29%	78%	22%	0%	20%	8%	25%	0%	42%	16%	0%	15%	Other
100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	Total %
1204	171	75	160	68	318	15	69	12	20	20	103	122	25	25	Total number reported

6.2.2.8 Equipment failure rate multiplier versus maintenance quality

The relationship between maintenance practice and equipment failures for transformers, circuit breakers, and motors is discussed in detail in IEEE Std 3006.4. These multipliers were determined in a special study (Part 6 of Patton [B32]) (*Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 61). The failure rate of motors is very sensitive to the quality of maintenance.

The percentage of failures due to inadequate maintenance versus the time since maintained is given in IEEE Std 3006.4 for circuit breakers, motors, open wire, transformers, and all electrical equipment classes combined. A high percentage of electrical equipment failures were blamed on inadequate maintenance if there had been no maintenance for more than two years prior to the failure.

6.2.2.9 Reliability improvement of electrical equipment in industrial plants between 1962 and 1973

The failure rates for electrical equipment (except for motor starters) in industrial plants appeared to have improved considerably during the 11-year interval between the 1962 AIEE reliability survey (see Dickinson [B6]) and the 1973-1974 IEEE reliability survey (see IEEE Committee Report [B13]). Table 36 shows how much the failure rates had improved for several equipment categories. These data are calculated from a 1974 report (Albrecht, et al. [B2]). In 1962, circuit breakers had failure rates that were 2.5 to 6.0 times higher than those reported in 1973. The largest improvements in equipment failure rates have occurred on cables and circuit breakers. The authors discussed some of the reasons for the failure rate improvements during the 11-year interval. It would appear that manufacturers, application engineering, installation engineering, and maintenance personnel have all contributed to the overall reliability improvement.

Table 36 —Failure rate improvement factor of electrical equipment in industrial plants during the 11-year interval between the 1962 AIEE survey and the 1973 IEEE survey

Equipment category	Failure rate ratio AIEE (1962) IEEE (1973)
Cable	
Nonleaded in underground conduit	9.7
Nonleaded, aerial	5.8
Lead covered in underground conduit	3.4
Nonleaded in aboveground conduit	1.6
Cable joints and terminations	
Nonleaded	5.3
Leaded	2.0
Circuit breakers	
Metal-clad drawout, 0 V to 600 V	6.0
Metal-clad drawout, above 600 V	2.9
Fixed 2.4 kV to 15 kV	2.5
Disconnect switches	
Open, above 600 V	3.4
Enclosed, above 600 V	1.6
Open wire	3.4
Transformers	
Below 15 kV, 0 kVA to 500 kVA[a]	2.0
Below 15 kV, above 500 kVA	2.0
Above 15 kV	1.6
Motor starters, contactor type	
0 V to 600 V	1.3
Above 600 V	1.3

[a] 300 kVA to 750 kVA for 1973.

The authors also make a comparison between the surveys of the actual downtime per failure for all the equipment categories shown in the table in IEEE Committee Report [B13]. In general, the actual downtime per failure was larger in 1973 than in 1962.

6.2.2.10 Loss of motor load versus time of power outage

A special study was reported in Table 47 of IEEE Committee Report [B13] (*Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 61) on loss of motor load versus duration of power outages. When the duration of power outages is longer than 10 cycles, most plants lose motor load. However, when the duration of power outages is between one and 10 cycles, only about one-third of the plants lose their motor load.

Test results of the effect of fast bus transfers on load continuity are reported in Averill [B5]. This includes 4 kV induction and synchronous motors with the following type of loads:

a) Forced draft fan

b) Circulating water pump

c) Boiler feed booster pump

d) Condensate pump

e) Gas recirculation fan

A list of prior papers on the effect of fast bus transfer on motors is also contained in Albrecht, et al. [B3].

6.2.2.11 Critical service loss duration time

What is the maximum length of time that an interruption of electrical service will not stop plant production? The median value for all plants is 10.0 s. See Table 2-3 in IEEE Std 3006.2-2016 for a summary of the IEEE survey of industrial plants.

What is the maximum length of time before an interruption to electrical service is considered critical in commercial buildings? The median value of all commercial buildings is between 5 min and 30 min. See Table 2-3 in IEEE Std 3006.2-2016 for a summary of the IEEE survey of commercial buildings.

6.2.2.12 Plant restart time

What is the plant restart time after service is restored following a failure that has caused a complete plant shutdown? The median value for all plants is 4.0 h. See Table 2-4 in IEEE Std 3006.2-2016 for a summary of the IEEE survey of industrial plants.

6.2.2.13 Other sources of reliability data

The reliability data from industrial plants that are summarized are based upon IEEE Committee Report [B16], which was published during 1973-1975. Dickinson's report [B6] is an earlier reliability survey of industrial plants that was published in 1962.

Many sources of reliability data on similar types of electrical equipment exist in the electric utility industry. The Edison Electric Institute (EEI) has collected and published reliability data on power transformers, power circuit breakers, metal-clad switchgear, motors, excitation systems, and generators (see EEI Publications [B33], [B34], [B35], [B36], [B37], [B38], [B39]). Most EEI reliability activities do not collect outage duration time data. The North American Electric Reliability Council (NERC) collects and publishes reliability and availability data on generation prime mover equipment.

Failure rate data and outage duration time data for power transformers, power circuit breakers, and buses are given in Patton [B32]. These data have come from electric utility power systems.

Very little other published data is available on failure modes of power circuit breakers and on the probability of a circuit breaker not operating when called upon to do so. An extensive worldwide reliability survey of the major failure modes of power circuit breakers above 63 kV on utility power systems has been made by the CIGRE 13-06 Working Group as shown in *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 161. Failure rate data and failure per operating cycle data have been determined for each of the major failure modes. Outage duration time data has also been collected. In addition, data has been collected on the costs of scheduled preventive maintenance; this includes the hours of labor per circuit breaker per year and the cost of spare parts consumed per circuit breaker per year.

IEEE Std 500-1984 [B18] is a reliability data manual for use in the design of nuclear power generating stations. The equipment failure rates therein cover such equipment as annunciator modules, batteries and chargers, blowers, circuit breakers, switches, relays, motors and generators, heaters, transformers, valve

operators and actuators, instruments, controls, sensors, cables, raceways, cable joints, and terminations. No information is included on equipment outage duration times.

The Institute of Nuclear Power Operations (INPO) organization operates the Nuclear Plant Reliability Data System (NPRDS), which collects failure data on electrical components in the safety systems of nuclear power plants. Outage duration time data is collected on each failure. The NPRDS database contains more details than IEEE Std 500-1984, but INPO has followed a policy of not publishing its data.

Very extensive reliability data have been collected for electrical and mechanical equipment used on offshore platforms in the North Sea and the Adriatic Sea (see OREDA-92 [B31]). This includes generators, transformers, inverters, rectifiers, circuit breakers, protection equipment, batteries, battery chargers, valves, pumps, heat exchangers, compressors, gas turbines, sensors, cranes, etc. Data have been published on failure rates, number of demands, failures per demand, repair time, and hours of repair labor. Ten oil companies have participated in this data collection over a period of nine years.

Annex A

(informative)

Bibliography

Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

[B1] Adler, R. B., et al., "An IEEE survey of U.S. and Canadian overhead transmission outages at 230 kV and above," *IEEE Transactions on Power Delivery*, vol. 9, no. 1, pp. 21-39, January 1994, http://dx.doi.org/10.1109/61.277677.[1,2]

[B2] Albrecht, P. F., et al., "Assessment of the reliability of motors in utility applications," *IEEE Transactions on Energy Conversion*, vol. EC-2, no. 9, pp. 396-406, September 1987, http://dx.doi.org/10.1109/TEC.1987.4765865.

[B3] Albrecht, P. F., et al., "Assessment of the reliability of motors in utility application—updated," *IEEE Transactions on Energy Conversion*, vol. EC-1, no. 3, pp. 39-46, March 1986, http://dx.doi.org/10.1109/TEC.1986.4765668.

[B4] Aquilino, J. W., "Report of transformer reliability survey—industrial plants and commercial buildings," *IEEE Transactions on Industry Applications*, vol. IA-19, no. 5, pp. 858-866, September/October 1983, http://dx.doi.org/10.1109/TIA.1983.4504299.

[B5] Averill, E. L., "Fast transfer test on power station auxiliaries," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-96, no. 3, pp. 1004-1009, May/June 1977, http://dx.doi.org/10.1109/T-PAS.1977.32415.

[B6] Dickinson, W. H., "Report of reliability of electrical equipment in industrial plants, part II: Application and industry," *Transactions of the American Institute of Electrical Engineers*, vol. 81, no. 3, pp. 132-151, July 1962.

[B7] Ekstrom, T. E., "Reliability/availability guarantees of gas turbine and combined cycle generating units," *Proceedings of 1994 IEEE Industry Applications Society Annual Meeting,* Oct. 2-5, 1994, Denver, CO, pp. 2209-2225.

[B8] Heising, C. R., et al., "Summary of CIGRE 13-06 Working Group world wide reliability data and maintenance cost data on high voltage circuit breakers above 63 kV," *Proceedings of 1994 IEEE Industry Applications Society Annual Meeting,* Oct. 2-5, 1994, Denver, CO, pp. 2226-2234.

[B9] IEEE Committee Report, "Cost of electrical interruptions in commercial buildings," *IEEE-ICPS Technical Conference Record,* 75-CH0947-1-1A, Toronto, Canada, May 5-8, 1975, pp. 124-129.

[B10] IEEE Committee Report, "Reasons for conducting a new reliability survey on power, rectifier, and arc-furnace transformers," *IEEE-ICPS Technical Conference Record,* May 1979, pp. 70-75.

[B11] IEEE Committee Report. "Reliability of electric utility supplies to industrial plants," *IEEE-ICPS Technical Conference Record,* 75-CH0947-1-1A, Toronto, Canada, May 5-8, 1979, pp. 70-75.

[B12] IEEE Committee Report, "Report of generator reliability survey of industrial plants and commercial buildings," *IEEE-ICPS Technical Conference Record*, CH1543-8-1A, May 1980, pp. 40-44.

[1] The IEEE standards or products referred to in Annex A are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.
[2] IEEE publications are available from The Institute of Electrical and Electronics Engineers (http://standards.ieee.org/).

[B13] IEEE Committee Report, "Report on reliability survey of industrial plants, Parts 1-6," *IEEE Transactions on Industry Applications,* Mar./Apr. 1974, pp. 213-252; Jul./Aug. 1974, pp. 456-476; Sep./Oct. 1974, p. 681.

[B14] IEEE Std 141™, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (*IEEE Red Book*™).

[B15] IEEE Std 242™, IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (*IEEE Buff Book*™).

[B16] IEEE Std 315™, IEEE Standard Graphic Symbols for Electrical and Electronics Diagrams.

[B17] IEEE Std 493™, IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (*IEEE Gold Book*™).

[B18] IEEE Std 500™-1984 (Reaff 1991), IEEE Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear-Power Generating Stations.

[B19] IEEE Std 841™-2001, IEEE Standard for the Petroleum and Chemical Industry—Severe Duty Totally Enclosed Fan-Cooled (TEFC) Squirrel Cage Induction Motors—Up to and Including 370 kw (500 hp).

[B20] IEEE Std 1366™, IEEE Guide for Electric Power Distribution Reliability Indices.

[B21] IEEE Std 3006.3™-2017, IEEE Recommended Practice for Determining the Impact of Preventative Maintenance on the Reliability of Industrial and Commercial Power Systems.

[B22] IEEE Std 3006.5™, IEEE Recommended Practice for Use of Probability Methods for Conducting Reliability Analysis of Industrial and Commercial Power Systems.

[B23] IEEE Std 3006.9™-2013, IEEE Recommended Practice for Collecting Data for Use in Reliability, Availability, and Maintainability Assessments of Industrial and Commercial Power Systems.

[B24] IEEE Std 3007.1™, Recommended Practice for the Operation and Management of Industrial and Commercial Power Systems.

[B25] IEEE Std 3007.2™, Recommended Practice for the Maintenance of Industrial and Commercial Power Systems.

[B26] McWilliams, D. W., A. D. Patton, and C. R. Heising, "Reliability of electrical equipment in industrial plants—Comparison of results from 1959 survey and 1971 survey," *IEEE-ICPS Technical Conference Record,* 74CH0855-71A, Denver, CO, Jun. 2-6, 1974, pp. 105-112.

[B27] NSWC 11, "The Handbook of Reliability Prediction Procedures for Mechanical Equipment," published by the Naval Surface Warfare Center (Carderock Division), May 2011.

[B28] O'Donnell, P., "Report of large motor reliability survey of industrial plants and commercial buildings," *IEEE Transactions on Industry Applications,* Parts 1 and 2, Jul./Aug. 1985, pp. 853-872; Part 3, Jan./Feb. 1987, pp. 153-158.

[B29] O'Donnell, P., "Report of switchgear bus reliability survey of industrial plants," *IEEE Transactions on Industry Applications*, vol. IA-15, no. 2, pp. 141-147, March/April 1979, http://dx.doi.org/10.1109/TIA.1979.4503629.

[B30] O'Donnell, P., "Survey of lower voltage breakers as found during maintenance," *IEEE Industrial and Commercial Power Systems Technical Conference,* 6-9 May, 1996, New Orleans, LA.

[B31] OREDA-92, *Offshore Reliability Data Handbook*, 2nd ed. Norway: OREDA, 1992.

[B32] Patton, A. D., "Determination and analysis of data for reliability studies," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-87, no. 1, pp. 84-100, January 1968, http://dx.doi.org/10.1109/TPAS.1968.292260.

[B33] "Report on Equipment Availability for 10 Year Period 1965-74," EEI Publication no. 75-50 (Prime Mover Generation Equipment).[3]

[B34] "Report on Excitation System Troubles—1975," EEI Publication no. 76-78, Dec. 1976. (Later data have also been published.)

[B35] "Report on Generator Troubles—1975, "EEI Publication no. 76082, Dec. 1976. (Later data have also been published.)

[B36] "Report on Metalclad Switchgear Troubles—1975," EEI Publication no. 76-82, Dec. 1976. (Later data have also been published.)

[B37] "Report on Motor Troubles—1975," EEI Publication no. 76-79, Dec. 1976. (Later data have also been published.)

[B38] "Report on Power Transformer Troubles—1975," EEI Publication no. 76-80, Dec. 1976. (Later data have also been published.)

[B39] "Report on Power Circuit Troubles—1975," EEI Publication no. 76-81, Dec. 1976. (Later data have also been published.)

[B40] "Summary of Replies to the 1982 Technical Questionnaire on Rotating Machinery (Motors 1000 hp and Up)," unpublished report at Doble Conference, Apr. 1982, Boston, MA.

[3] These data are now collected and published by the North American Electric Reliability Council (NERC). NERC publications are available from the North American Electric Reliability Corporation (http://www.nerc.com/).

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